NEUROANATOMICAL AND ENVIRONMENTAL FACTORS PREDICTING READING SKILL DEVELOPMENT

By

MARK A. ECKERT

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1998

Dedicated to my Dad.

ACKNOWLEDGMENTS

I would like to express my sincere thanks to everyone who helped me with this dissertation. Specifically, I would like to thank Dr. Linda Lombardino, who made this dissertation possible; Wendy Swearingin, Angie Lane, and Marina Santarpia, to whom I am indebted for their personal support and help with the early stages of this project; my dissertation committee, whose advice helped to fortify this dissertation; the entire Leonard lab; and all my friends and family for their support and encouragement.

My resounding gratitude and admiration go to Dr. Christiana Leonard. I could not have imagined a better mentor.

Finally, I would like to thank my parents, whose model of love, strength and commitment has forged the person I have become, enabled me to reach my goals and appreciate this accomplishment.

TABLE OF CONTENTS

ACKNOWLEDGMENTS iii

LIST OF TABLES vi

LIST OF FIGURES viii

ABSTRACT x

REVIEW OF LITERATURE 1

- Phonological and Reading Development 2
  - Phonological Processing: A Building Block for Reading 2
  - Defining Reading Impairment 7
  - Socioeconomic Influences on Phonological Processing Skills 8
- The Heritability of Phonological Processing Skills 10
- The Neurobiology of Language 14
  - Cerebral Asymmetry: Language Dominance and Performance 25
- Nature and Nurture Models For Reading Development 37
- Dissertation Goals 41

METHODOLOGY 45

- Project Time Line 45
- Participants 46
  - Recruitment 46
- Behavioral Assessment 51
  - Phase I 51
  - Phase II 52
  - Phase III 53
- MRI Protocol and Measurement Method 54
  - MRI Acquisition 54
  - Quantification of Brain Structure 55
- Statistical Analysis 59

RESULTS 60

Path Presentations of Significant Correlations 61
Socioeconomic Status 61
Neuroanatomical Hemispheric Asymmetry 63
Hypothesis Testing 67
    Hypothesis 1 67
    Hypothesis 2 71
    Hypothesis 3 73
    Hypothesis 4 92
    Hypothesis 5 93
    Hypothesis 6 102

DISCUSSION 114

Behavioral Associations 115
    Kindergarten Spelling Predicts Future Phonological Skill 115
    Predictors of Behavioral Performance 117
    Heritability 119
    Hand Preference 120
Neuroanatomic Predictors of Reading Skill Development 122
    Kindergarten and 1st Grade Results 122
    6th Grade Results 124
    Exploratory Inferior Frontal Gyrus Results 132
    Change in Reading Performance from Kindergarten to 6th Grade 134
    A Role for the Right Hemisphere 138
    A Comparison to Previous Planar Asymmetry Studies 140
    The Non-Right Handed Effect 141
    Oral Language Impairment vs. Dyslexia 143
Nature and Nurture Contributions to Reading Development 144
    Individual Differences 144
    Race and SES 148
Technical and Methodological Considerations 149
General Summary 151

APPENDIX A PARENT INFORMATION LETTER 152

APPENDIX B INCOME LEVELS FOR SCHOOL LUNCH 154

APPENDIX C RESULTS DATA 155

LIST OF REFERENCES 164

BIOGRAPHICAL SKETCH 181

LIST OF TABLES

Table page

1-1. Regions of Activation for Functional Imaging Studies of Word Generation . . . 19
1-2. A Comparison of Dyslexia Imaging Studies . . . 34
1-3. Hypothesis 1 . . . 42
1-4. Hypothesis 2 & 3 . . . 42
1-5. Hypothesis 4 . . . 43
1-6. Hypothesis 5 . . . 43
1-7. Hypothesis 6 . . . 44
2-1. Explanations for Non-Participation Among the 49 Children Remaining in Alachua County . . . 48
2-2. Demographic Characteristic of Children Who Did Not Participate by Type of Explanation . . . 49
2-3. Sample Characteristics Across the Three Phases of this Project . . . 50
2-4. Intra-rater and Inter-rater Reliability for Neuroanatomical Measurements . . . 58
3-1. Hemispheric Asymmetry of the Neuroanatomical Variables . . . 65
3-2. Hemispheric Asymmetry of Neuroanatomical Variables in Right Handed Children . . . 66
3-3. Hemispheric Asymmetry of Neuroanatomical Variables in Non-Right Handed Children . . . 66
3-4. Multiple Regression Model Results for Hypothesis 1 . . . 68
3-5. Multiple Regression Coefficients for Hypothesis 1 . . . 68
3-6. Anatomical Correlations with Phase 2 Woodcock-Johnson Reading Tests of Achievement for Right Handed Subjects (N=21) . . . 72
3-7. Anatomical Correlations with Phase 2 Woodcock-Johnson Reading Tests of Achievement for Right Handed Subjects (N=12) . . . 72
3-8. Summary of Significant Neuroanatomical and Phase III Reading Skill Correlations by Hand Preference Group and Lunch Subsidy Grouping . . . 74
3-9. Coefficients for Regression Analysis of the Phonological Factor . . . 86
3-10. Neuroanatomical Variables Demonstrating Redundancy with PHR . . . 90
3-11. ANOVA Results Comparing the Planar Asymmetry of Right Handed Children with Low vs. High Reading Skills Across Development 94
3-12. Regression Results Predicting Phonological Change . . . 97
3-13. Regression Results for Control Neuroanatomical Variables and the Respective Hand Preference Interaction Terms Predicting the Index of Phonological Change . . . 101

3-14. Neuroanatomical Correlations with Speech Production and Naming Tasks Among Right Handed Children 104
3-15. Neuroanatomical Correlations with Speech Production and Naming Tasks Among Non-Right Handed Children 105
3-16. Regression Analysis Results Predicting Category Fluency 106
3-17. Regression Analysis Results Predicting Naming Speed 110
3-18. Summary of Results for Each Hypothesis 112
Appendix B
B-1 1997-1998 Lunch Subsidy Income Levels 154
Appendix C Results Data
C-1 Phase I Descriptive Statistics for the Early Reading Screening Inventory Subtests and Total Score 155
C-2 Phase II Woodcock-Johnson Tests of Achievement (raw scores) Descriptive Statistics 155
C-3 Phase III Behavioral Test Descriptive Statistics 155
C-4 Phase III Neuroanatomical Data Descriptive Statistics 157
C-5 Lunch Subsidy Correlation with Behavioral Assessment 157
C-6 Significant Correlations Between Neuroanatomical Measures and Lunch Status Among Children With a Right Hand Preference 159
C-7 Multiple Regression Predicting Phase 2 Word Attack Performance in Children with a Right Hand Preference (n=22) 160
C-8 Multiple Regression Predicting Phase 2 Word Identification Performance in Children with a Right Hand Preference (n=22) 160
C-9 Multiple Regression Predicting Phase 2 Passage Comprehension Performance in Children with a Right Hand Preference (n=22) 160
C-10 Phase 3 (sixth grade) Correlations Between Neuroanatomical and Reading Skill Variables in Right Handed Children (n=27) . 161
C-11 Phase 3 (sixth grade) Correlations Between Neuroanatomical and Reading Skill Variables in Right Handed Children Not Receiving Lunch Subsidy (n=17) 161
C-12 Phase 3 (sixth grade) Correlations Between Neuroanatomical and Reading Skill Variables in Right Handed Children Receiving Lunch Subsidy (n=10) 158
C-13 Phase 3 (sixth grade) Correlations between Neuroanatomical and Reading Skill Variables in Non-Right Handed Children (n=12) 159
C-14 Hypothesis 5 ANOVA Results for all Subjects in the Low vs. High Reading Skill Development Groups 162

LIST OF FIGURES

Figures Page

1-1 Sagittal Image of the Human Brain 18
2-1 Project Time Line 45
3-1 Behavioral Relationships 62
3-2 Hours of Parental Homework Help by Lunch Status Groups 64
3-3 Socioeconomic Effects on Kindergarten Spelling Performance 69
3-4 The Relationship of Kindergarten Spelling Performance to Motor Bank Asymmetry 70
3-5 The Relationship of Phoneme Reversal to Planar Asymmetry by Hand Preference and Socioeconomic Status 75
3-6 The Relationship of Phoneme Reversal to Planar Asymmetry in Right and Non-Right Handed Children Not Receiving Lunch Subsidy 76
3-7 The Relationship of Phoneme Reversal to Planar Asymmetry in Right Handed Children by SES (Lunch Subsidy) 77
3-8 The Relationship of Phase III Word Identification to Planar Asymmetry by Hand Preference and Lunch Status 78
3-9 The Relationship of Phase III Passage Comprehension to Planar Asymmetry by Hand Preference and Lunch Status 79
3-10 The Relationship of Phase III Word Attack Performance to Planar Asymmetry by Hand Preference and Socioeconomic Status (Lunch Subsidy) 80
3-11 The Relationship of Phase III Lindamood Auditory Conceptualization Task to Planar Asymmetry by Hand Preference and Lunch Status 81
3-12 The Relationship of WISC Information to Planar Asymmetry by Hand Preference and Lunch Status 83
3-13 The Relationship of FSIQ to Planar Asymmetry by Hand Preference and Lunch Status 85
3-14 The Relationship of the Index of Phonological Awareness to Planar Asymmetry by Hand Preference and Lunch Status 87
3-15 Neuroanatomical, SES, and Hand Preference Prediction of Phonological Awareness 88
3-16 Difference in Planar Asymmetry Between Phonological Developmental Groups 95
3-17 The Relationship of Phonological Change Between Kindergarten and 6th Grade To Planar Asymmetry Among Children with a Right Hand Preference 95

3-18 The Ascending Ramus of the Planum Temporale Predicts the Index of Phonological Change in Both Hand Preference Groups 98
3-19 The Horizontal Ramus of the Planum Temporale Precits the Index of Phonological Change in Right Handed Subjects 99
3-20 The Relationship of Category Fluency to Inferior Frontal Gyrus Asymmetry 103
3-21 The Relationship of Category Fluency to Planum Temporale (Ascending Ramus) Asymmetry 107
3-22 The Relationship of Letter Naming Speed to Planum Temporale (Ascending Ramus) Asymmetry 108
3-23 The Relationship of Number Naming Speed to Planum Temporale (Ascending Ramus) Asymmetry 109
3-24 Significant Paths Among Behavioral and Anatomical Variables 113
4-1 A Path Model of Congruent Asymmetry 129

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

NEUROANATOMICAL AND ENVIRONMENTAL FACTORS PREDICTING READING SKILL DEVELOPMENT

By

Mark A. Eckert

December, 1998

Chairperson: Christiana Leonard, Ph.D.
Major Department: Psychology

Although socioeconomic status (SES) is a strong predictor of academic achievement and reading skills, there are individual differences in reading skills that remain unexplained. Oral language impairment and awareness of speech sounds in normal children has been predicted by neuroanatomy, and specifically planum temporale asymmetry (PHRA). However, it is not clear whether brain structure can place limits on the development of phonological awareness, reading, and speech production throughout childhood. The primary goals of this longitudinal study were to 1) confirm the relationship of children's phonological awareness to PHRA and 2) establish if the rate of phonological development can be predicted by PHRA. Thirty-nine children from the Alachua County public school system were assessed for their reading skills in kindergarten and 6th grade. Reading skills were related to neuroanatomical measures obtained from a 6th grade MRI. Multiple regression demonstrated a significant contribution of PHRA, hand preference, a PHRA-hand preference interaction (PHRA-H), and SES to 6th grade reading skill (R=.771, p<.001). The rate of reading skill development was also predicted by PHRA, hand preference and PHRA-H (R=.628, p=<.001). However, the effect of brain structure was not specific to planar asymmetry. Central sulcus asymmetry also predicted reading skill performance and the rate of development. All relationships were strongest for children from low SES families. The environmental and genetic advantages provided by a high SES family may compensate for the cognitive disadvantage of brain asymmetry that is not congruent with the direction of hand preference. The results suggest that environmental and biological risk factors interact to produce reading failure.

CHAPTER 1
REVIEW OF LITERATURE

Approximately three to twenty percent of English speaking children experience difficulty learning to read (Shaywitz, 1996). A primary concern of those in the area of reading development is identifying children who are at risk for reading problems before the onset of reading acquisition and those children who have reading deficits that will persist through out the elementary school years (Juel and Leavell 1988; Slavin, 1985). Intervention programs do help some children, but not all. It has been assumed that children who do not benefit from reading remediation have "constitutional" or genetic and neuropathological abnormalities (Vellutino et al., 1996).

This review of the literature will introduce phonological processing as a strong predictor of reading performance and development, define reading and language impairment, examine the genetics of reading disability, review the current understanding of the biological basis of language, and evaluate the evidence for neuroanatomical correlates of language and phonological skill. The evidence for environmental and biological contributions to reading development provide the rationale for this study.

The major objectives of this study were to (1) confirm evidence of a relationship of brain structure to oral language skills, (2) determine if structural variability in the language areas of the brain constrain or facilitate the development of reading and oral language skills, (3) determine whether brain structure differentiates children who make greater strides in reading development than other children, (4) and to examine exploratory relationships of brain structure to speech production.

Phonological and Reading Development

Phonological Processing: A Building Block for Reading

Learning to read requires that children recognize letters and pair those letters with sounds in order to decode the sounds of words. The skills necessary to accomplish the decoding and recoding task of reading are defined under the umbrella term phonological processing. Phonological processing includes the ability to represent sound characteristics of spoken and written words as individual units of sounds, or phonemes. Therefore, the use of oral language skills to decipher written language provides a critical strategy for the development of literacy.

Phonological processing includes three general phonological skills: phonological awareness; phonetic recoding in working memory; and phonological recoding in lexical access. These skills are strong predictors of reading performance in children and adults (Byrne et al., 1996; Pennington et al., 1990; Lombardino et al., 1997). Failure to acquire these skills is thought to contribute to reading problems (Denckla and Rudel, 1976; Bradley and Bryant, 1983; Wagner et al., 1997; Torgesen et al., 1989; Felton et al., 1990; Shankweiler, 1995; Stanovich 1988; Stanovich et al., 1984).

Phonological awareness (PA) is the conscious detection of the basic sound units of speech and the ability to manipulate those units of speech. Different measures of PA, that range in complexity, have all demonstrated strong associations to reading performance (Bradley and Bryant, 1983; Felton et al., 1990; Liberman, 1974). PA develops at approximately the time that children begin to learn to read (Wagner et al., 1997). However, there is evidence that pre-reading children have a basic awareness of speech sounds (Fox, 1975).

More complex phonological tasks and learning to pair symbols with speech sounds require the use of some form of memory. This ability requires phonetic recoding in working memory, or maintaining letter-sound information in some working memory system in order to perform some operation on the information. Phonetic recoding in working memory tasks require an individual to retain verbal information presented as an auditory or visual stimulus and then recall that information (Torgesson & Wagner). Digit span serves as a good example of phonetic recoding in working memory.

Difficulty maintaining information in working memory may impair the ability to decode words but also the ability to find meaning in a sentence. A child might not have sufficient resources to decode all the words in a sentence and then put them together to find meaning in the sentence (Berent, 1995). Poor readers usually recall fewer digits, words, letters or non-words on short term memory tasks than do good readers (Shankweiler, 1995).

Learning to read not only requires using symbols to represent speech sounds and a good working memory for verbal information, but also the ability to rapidly access the phonological representations of orthographic symbols. Phonological recoding in lexical access is the transformation of graphemes to phonemes in order to translate a written word into its oral representation (Liberman, 1974; Wagner et al., 1997). This form of phonological processing has also been defined as the rapid retrieval of phonological code to articulate a word or sound (Denckla, 1976). Rapid naming tasks are used to assess phonological recoding in lexical access. These tasks involve naming a series of digits, colors or letters as quickly as possible. The speed and accuracy with which children can produce the items is highly predictive of reading disabilities (Denckla, 1976) and achievement (Wolf, 1991; Cornwall, 1992; Felton et al., 1990).

Rapid naming is predictive of reading measures during the early stages of reading development in normal children. However, the association between rapid naming and reading performance disappears with age in children who are normal and moderately impaired readers (Wolf et al., 1986). Rapid naming appears to be an important early predictor of reading development among low average to superior readers.

Children with severe reading impairment often present with phonological awareness and rapid naming problems into later stages of reading development (Bowers and Wolf, 1993). McBride-Chang (1996) examined the reading skills of a group of poor readers that were at or below the 25th percentile and a group of good readers scoring at or above the 50th percentile on a test of non-word decoding. Phonological awareness was significantly related to all of the measures for children in each group. However, speeded naming was correlated with reading performance only in the poor reading group. Good readers did not demonstrate a significant relationship between reading and speeded naming. The data suggest that reading impaired children have problems accessing the lexicon to produce speech either because it has not become proceduralized or because they are less efficient at recognizing words (Ehri, 1989).

Summary of phonological processing skills

Phonological processing (PA) is highly predictive of reading success. PA is a strong predictor of present and future reading success. PA is also capable of differentiating good readers from impaired readers. Phonological recoding in lexical access is also predictive of reading success, but only during the early stages of reading development in normal children. Children with severe reading impairments demonstrate both phonological awareness and rapid naming deficits throughout childhood. This problem may be a failure to automatize reading common items and/or be the result of memory problems. Children with reading deficits can also have deficits specific to verbal memory or phonological recoding in working memory. The evidence suggests that reading-impaired children do not have a general memory impairment.

Phonological processing: critical to reading development

There has been some controversy as to whether reading development causes growth in phonological processing skills, phonological processing causes advances in reading development, or each skill has positive influences on the other (Torgesen et al., 1994). To address the question of causal direction, pre-reading assessments of phonological processing have been performed to determine if phonological skills are predictive of future reading success and training studies have been performed to determine if phonological training has positive influences on learning to read. The evidence that has accumulated from both research paradigms does suggest that phonological awareness has a causative influence on reading development.

Pre-reading phonological processing

Blachman (1991), Stanovich et al. (1984), Ehri (1989), Share (1995), Torgesen et al. (1994), and Lombardino et al. (in press) have all shown that pre-reading skills are significantly related to early reading achievement. Pre-reading skills include letter knowledge, word recognition, and invented spellings. Invented spellings is a phonological awareness task that involves spelling a series of words after hearing the word spoken. Invented spelling requires that the child break the word down into its component sounds and then select the correct alphabetic symbols for those sounds.

In phase I of the Lombardino et al. (in press) study, 149 children in kindergarten were given the Early Reading Screening Inventory (ERSI). The ERSI includes subtests of invented spellings, word recognition and letter knowledge. In phase II of the study, the same children were given three standardized measures of reading performance when they were in first grade and had begun formal reading instruction. The results showed that word recognition and invented spellings were strong predictors of reading performance in the first grade. Therefore, the awareness of speech sounds prior to formal reading instruction may have influenced the ease with which early reading developed.

Defining Reading Impairment

There are many different labels used to separate children into different reading impairment groups. Inclusion in a phonological dyslexia group defines a person as having difficulty producing and representing phonological stimuli. This phonological problem can be associated with memory deficits (Shankweiler, 1995), and occurs in the presence of normal IQ and comprehension of oral language (Shaywitz, 1996). Surface dyslexia includes people with normal IQ and phonological skills that have difficulty identifying irregular words. Phonological and surface dyslexics are considered to have written language deficits. Garden variety language or reading impairment includes people with phonological, IQ, comprehension, and speech production deficits. People with language impairment are considered to have both written and oral language deficits.

The most common factor associated with reading deficits is socioeconomic status (MacDonald & Cornwall, 1995). Children from low socioeconomic environments perform worse than children from higher socioeconomic backgrounds. These children probably include many garden variety language impaired children. However, within low and high socioeconomic strata there may be a number of factors influencing language and reading deficits.

Theories of reading impairment suggest that the primary cause is an auditory deficit that is also demonstrated in the phonology of language (Reed, 1989; Watson, 1992), a problem processing rapid acoustic information (Tallal, 1973), or the result of deficits specifically in the speech domain (Mody et al., 1997). The discrepancy in findings and development of multiple theories most likely stem from the inclusion of a variety of different types of language impairment. Scientific literature and social policy most frequently distinguish between dyslexia and language impairment, although there are probably subgroups with in each group.

The common deficit among the phonological dyslexics and the garden variety language-impaired is a phonological awareness deficit. The range of cognitive performance among the groups has also been viewed as evidence for one basic deficit along a continuum (Shaywitz, 1996). However, in addition to the IQ differences, perceptual and processing speed deficits can be found in clusters of reading impaired patients even within a diagnosis such as phonological dyslexia (Lombardino et al., 1998). Nonetheless, the oral vs. written language distinction between dyslexic and language impaired populations becomes critical when evaluating the evidence for neuroanatomical correlates to language and reading performance. Verbal ability, not specifically phonological impairment, seems to be critical when distinguishing reading-impaired groups based on their neuroanatomy (Rumsey et al., 1997).

Socioeconomic Influences on Phonological Processing Skills

Factors related to SES are strongly predictive of academic achievement. As expected, low SES is also reported to be related to poor phonological performance in children and adults. Cornwall (1992) and Oerlemans & Dodd (1993) have both reported significant relationships between SES and spelling, phonological decoding, single word reading and passage comprehension. In addition, a study of phonological skills in adults showed that adults with a history of reading disability were more likely to be from a low SES background (Felton et al., 1990).

Racial groups are disproportionately represented in different SES groups. This is often a confound in interpreting SES effects on academic achievement. However, SES effects on achievement are independent of race. A study of 72 African American pre-school children demonstrated a significant effect of SES on phonological skills. Even more interesting was that low SES children were beginning to exhibit two dialects compared to a single dialect exhibited by middle SES children (Ratusnik and Koenigsknecht, 1975). Therefore, cultural influences related to a low SES, not race itself, appear to be affect the development of oral language and reading skills.

The Ratusnik study suggests that the style of communication which dominates a child's developmental environment has considerable influence on the successful acquisition of phonological skills. There is also evidence to suggest that distinctive interaction styles affect cognitive development (Snow, 1983; Peralta de Mendoza, 1995). Children that develop good verbal skills have mothers who use a more elaborate style of language than the style used by low SES mothers.

If parental style of communication has an influence on child development, then it is not surprising that parental education is related to reading skill and academic achievement (Baydar et al., 1993). Parents with less education are reported to have fewer books in the home, another variable related to academic achievement (Blatchford and Farquhar, 1988). Exposure to print is critical for acquiring early reading skills (Adams, 1990).

Clearly, the home environment created by parents has a dramatic impact on children's development. However, the home environment is not a pure environmental variable. The genetics of one generation influence the environment for the children of the next generation.

The Heritibility of Phonological Processing Skills

Intervention studies show that intensive training can help children with difficulty in reading. Children who benefit from remediation are often from low SES backgrounds. However, there are some children for whom intervention is not beneficial. Constitutional explanations for reading problems suggest there are genetic influences on reading development or skills required for reading.

The inheritance of reading problems has been observed and documented for many years (Hallgren, 1950). Evidence from behavioral genetics research suggests that reading disability is moderately heritable and transmitted at a major chromosomal locus (Olson et al., 1989; Smith et al., 1990; DeFries, 1993; Cardon et al., 1994; Grigorenko et al., 1997). Quantitative trait loci (QTL) for reading disability have been proposed to be found on at least 3 different chromosomes.

The field of behavioral genetics traces behavioral deficits through family histories or by examining the concordance rates of behaviors or disabilities among twins. Recently, behavioral genetics has been coupled with chromosomal typing of families and twins.

Therefore, it is possible to examine common chromosomal markers among twins who have the same behavioral traits and family members who do or do not have common behavioral traits in order to determine the potential chromosomal locus of the trait.

DeFries et al. (1987) examined the heritability rates of reading disability in monozygotic (MZ) and dizygotic (DZ) twins. The results were similar to most twin studies (Plomin and Loehlin, 1989). All twins had high rates of similarity in their reading performance. However, the MZ twins performed more similarly than DZ twins. The heritability rate for reading disability among MZ twins was estimated at 50-70%.

Olson et al. (1989) attempted to determine which reading skills were heritable. Phonological coding (rapid naming of non-words) and orthographic coding (word recognition of pseudohomophone pairs) were assessed in a group of 172 twins and affected siblings and 172 matched normal twins and siblings. Phonological coding was found to have a high degree of heritability. However, there was no evidence that orthographic coding was heritable.

Pennington and Smith (1997) propose that the population range of reading performance and reading deficits are not a function of one major gene, but more likely to a polygenic form of transmission. Multiple QTLs have been associated with reading disability. These QTLs include the Rh region of chromosome 1 (Grigorenko et al. 1997), chromosome 15 (Lubs et al. 1988; Grigorenko et al. 1997), and chromosome 6 (Smith et al., 1990; Cardon et al. 1994; Grigorenko et al. 1997). However, only evidence for chromosome 6 has been replicated and the evidence for chromosome 15 is conflicting.

Smith et al. (1990) were first to localize a marker for reading disability to chromosomes 6 and 15. Cardon et al. (1994) from the same group replicated the chromosome 6 finding in a different sample. Convergent evidence for the chromosome 6 (p21.3) was found in 114 sib pairs, 50 DZ twin pairs, and DZ children and kindred siblings with extreme reading disability. However, chromosome 15 was not replicated as a significant marker for reading disability.

Grigorenko et al. (1997) also replicated the finding of chromosome 6 as the QTL for reading disability. Their sample included 6 extended families, with at least 4 dyslexics in each family. This is a unique study in that the phenotype for reading was examined at different levels of complexity. At the most basic level, phonological awareness was assessed using the Lindamood Auditory Conceptualization task (LAC) and the Woodcock-Johnson (WJ) Word Attack subtest. At the next level, recoding in lexical access was assessed with rapid automatic naming. Finally, word reading was assessed with the Word Identification subtest of the WJ. Genetic analyses included chromosomal regions 6p23-p21.3 and 15pter-qter because of their previous associations with reading disability, and 16pter-qter as a control region. Chromosome 6 was related only to phonological awareness. Single word reading and recoding in lexical access had no association with chromosome 6. However, chromosome 15 was uniquely associated with single word reading. The control, chromosome 16, was not associated with any phenotype.

The double dissociation of QTLs for specific behaviors is suggestive of modularity of function. However, Pennington & Smith (1997) make the point that "the QTLs influencing dyslexia that appear to be dominant on chromosomes 6 and 15 are not genes for dyslexia or reading skill, but only genes that somehow lead to a disruption in epigenesis and development that eventually alters learning to read." p(15).

The chromosome 15 and 6 QTLs have also been correlated to a host of other developmental problems or disorders such as autism, developmental delay, hydrocephalus, craniofacial malformations (Davies et al., 1996) and Angelman syndrome (Repetto et al., 1998). In addition, a homologue to the mouse gene required for neural tube formation has also been mapped to position 6p24-6p23 (Berge-Lefranc et al., 1996). These data suggests that chromosomes 15 and 6 have a role in central nervous system development and may produce structural differences that could serve as markers for language impairment.

Indirect support for genetically related structural differences on reading function was reported by Wood (1997). Reading impaired subjects with chromosomal markers for their impairment produced a different pattern of brain activation for Positron Emission Tomography (PET) language tasks than their unaffected family members (Wood, 1997). Different patterns of activation could reflect a different neural architecture.

Evidence for a genetic-neuroanatomical-behavioral correlation has also been reported in the KE family. This family has a severe articulation problem affecting expressive language, grammar and orofacial dyspraxia (Vargha-Khadem & Passingham, 1990). Affected family members exhibit a marker on chromosome 7 for their deficits. The affected family members were also found to have caudate nuclei that were significantly smaller than those of unaffected family members (Watkins, 1997).

Summary. The genetic data suggest that reading skill deficits run in families. There is evidence from genetic linkage analysis that there are chromosomal markers for skills such as phonological awareness and single word reading. The linkage studies imply that specific alleles are responsible for variability in reading skill and reading comprehension. The possibility exists that these chromosomal markers may include genes that are responsible for the neural organization of neuroanatomical structures involved in processing linguistic information.

The Neurobiology of Language

During the 19th century, Marc Dax, Paul Broca and Karl Wernicke observed that damage occurring in the left hemisphere of the brain was more likely to cause expressive and receptive language impairment than right hemisphere damage (Luria, 1962). The observation that the brain is functionally lateralized for language has been repeated numerous times. Electrophysiology, the WADA test, studies of patients with brain lesions, and functional imaging data support the concept of a functionally lateralized brain.

Not every brain is organized so that language is dominated by the left hemisphere. Right hemisphere lesions produce aphasia in some people. However, the number of people with right hemisphere dominance for language is small. And those who do have a right hemisphere dominance are more likely to be left-handed (Luria, 1962).

Handedness is strongly related to hemispheric representation for language and is another example of laterality. Approximately 90% of the population is reported to be right-handed (Annett, 1970). Among right-handed people it is estimated that 95% are left hemisphere dominant for language. Left hemisphere dominance for language is believed to occur in 70% of non-right-handed people. The remaining 30% non-right-handed and 5% of right-handed people are believed to have either bilateral or right hemisphere representation for language (Rasmussen, 1975).

Language dominance

The population rates of hemispheric dominance for expressive speech were determined by anesthetizing one hemisphere of the brain and then assessing language performance. The sodium amytal test or the WADA test determines hemispheric representation for language in epilepsy patients who are candidates for surgery. The WADA is done to determine how surgery may impair cognitive functioning by determining which hemisphere is dominant for language. An injection of a barbituate into the left or right carotid artery momentarily impairs activity on the side of injection. Following the injection the patient is asked to repeat a sentence, answer questions, read, or count. If the patient has production deficits following injection to one side of the brain, then the assumption is that the other hemisphere cannot sustain speech.

Rasmussen and Milner (1975) found that most patients had counting difficulty following a left hemisphere injection. Right hemisphere injection did not impair repeating or reading except in the small number of individuals assumed to have bilateral or right hemisphere representation for language. This result suggests that it is very unusual for the use of language to be dominated by the right hemisphere. Epilepsy patients who do exhibit right hemisphere dominance for language are often patients with left temporal lobe epilepsy that had an onset before language began to develop (Strauss & Goldwater, 1992).

The WADA results support aphasia studies suggesting a left hemisphere dominance for language. However, language localization should probably not be thought of as being dichotomous. Binder et al. (1996) showed that asymmetry of activation during a single word semantic decision task was strongly correlated with WADA results. But, they also showed that while the left hemisphere was dominant for language tasks, the right hemisphere was also activated to varying degrees across subjects. Right hemisphere activation might be related to paralinguistic functions, but does not preclude the notion that there can be varying degrees of lateralization for expressive or receptive speech.

Language production

Epilepsy, stroke, tumor, and head trauma provide unfortunate replications of Broca's observation that language is impaired when the anterior left hemisphere is damaged (Luria, 1962). Right hemisphere damage rarely impairs language performance, but can impair visuo-spatial performance (Heilman et al., 1986). Neurological cases involving the left hemisphere also demonstrate a division of labor within the left hemisphere and around the sylvian fissure. Broca's and Wernicke's aphasia are the two classic aphasias that represent a geographical distinction in language function.

Broca's aphasia is the inability to produce speech, with at least moderately preserved speech perception. Dax and Broca reported that damage to the inferior frontal gyrus, or Broca's area, produces speech production problems. Broca's area includes pars triangularis and pars opercularis or Broadmann's areas 44 and 45. Pars triangularis is believed to be the principal anterior speech region because damage impairing speech production almost always includes pars triangularis (Leonard, 1997) (see figure 1-1).

The exact role or roles of Broca's area is unclear. Damage occurring in the inferior frontal lobe impairs the fluency of all patients to some degree. Broca's aphasics also demonstrate problems with grammar (Blumstein, 1994), speech can be telegraphic, there are deficits decoding the phonological structure of speech (Blumstein, 1994), and working memory for verbal material can be impaired (Baddeley, 1995).

Goldman-Rakic (1990) has shown that area 7 or primate homologous parietal cortex is composed of maps for spatial information. The spatial maps are maintained in connections with the principal sulcus of the frontal lobe. Neurons in the principal sulcus retain the information after neurons in area 7 are no longer active. If neurons in the principal sulcus are damaged, then impaired working memory is found for spatial tasks and prevents the motor output to complete a working memory task (Goldman-Rakic, 1990). Broca's area may have a similar organization. Functional imaging work in humans supports the idea that the inferior frontal gyrus is a complex of language processing structures responsible for retaining verbal material in working memory and planning speech production (Paulesu et al., 1997).

Functional imaging studies have also been designed to determine the brain regions used for generating speech. These studies replicate the lesion data by finding activation of the inferior frontal gyrus for production tasks. Table 1-1 presents the type of speech production tasks that have elicited activation in the inferior frontal gyrus. The Talairach

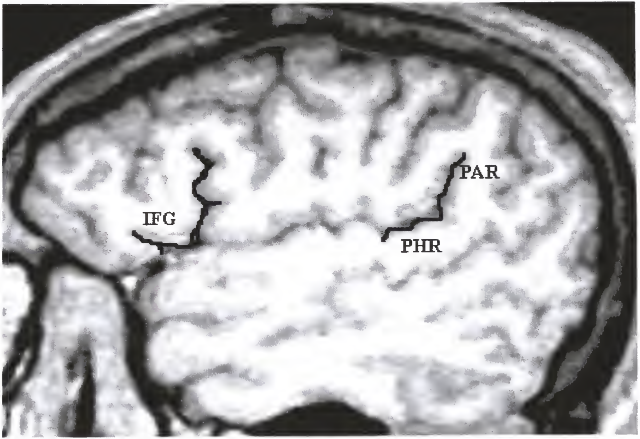


Figure 1-1. Sagittal Image of the Human Brain Outlining the Inferior Frontal Gyrus (IFG), or Broca's Area, and the Horizontal (PHR) and Ascending (PAR) Branches of the Planum Temporale, or Wernickes Area.

Table 1-1. Regions of Activation for Functional Imaging Studies of Word Generation.

Task	Method	Talairach Coordinates X : Y : Z	Authors
Category-word generation	fMRI	-36 : 24 : 16 -30 : 20 : 12	Paulesu et al. (1997)
Letter-word generation	fMRI	-36 : 24 : 16 -36 : 6 : 16	Paulesu et al. (1997)
Semantic category judgement	fMRI	-42 : 22 : 20	Vandenberghe et al. (1996)
Subvocal rehearsal	fMRI	-46 : 2 : 16 48 : 4 : 12	Paulesu et al. (1993)
Word generation	PET	-28 : 50 : -6	Petersen et al. (1988)
Naming animals Naming tools	PET	-41 : 22 : 3 -45 : 22 : 9	Damasio et al. (1996)
Inner speech: Self Imaginary	PET	-32 : 20 : 16 -38 : 14 :12	McGuire et al. (1996)
Word generation to noun	PET	-28 : 50 : -6	Petersen et al. (1990)
Word generation to noun	PET	-40 : 14 : 16	Wise et al. (1991)
Noun Generation	PET	-42 : 24 : 24 44 : 14 : 4	Warburton et al. (1996)

coordinates are also presented to provide a positional reference for the activation. There is some consistency in the areas of activation despite the many confounds associated with different functional imaging paradigms. Word generation for letters is more frequently associated with activation of the medial and posterior inferior frontal gyrus region or the pars opercularis. Word generation for category items such as animals or vegetables is more often associated with activation of more anterior regions of the inferior frontal gyrus, including the pars triangularis.

An animal model for speech production

Asymmetry for vocal communication is not unique to humans. Song birds exhibit similar communication impairments as humans following a unilateral lesion. Cutting the left hypoglossal nerve, which is controlled by the left hemisphere, inhibits canary singing. However, cutting the right hypoglossal does not inhibit singing (Nottebohm, 1976). Therefore, the motor output for song bird communication is asymmetrically controlled.

This effect is reversed in the Zebra finch. Cutting the right hypoglossal or a lesion to the right forebrain caudal hyperstiratum ventrale or higher vocal center (HVC) impairs singing, particularly the control of temporal patterning for songs. Lesions to the left hypoglossal or HVC have much less of an effect on singing performance (Williams et al., 1992). Nottebohm suggests that the direction of the asymmetry is not important, but that hemispheric dominance is important for function. However, bird song might not be completely analogous to functional lateralization for human speech. Peripheral factors, such as size differences in the left and right syrinx could explain bird song laterality (Konishi, 1985).

Receptive language

Damage to the posterior left hemisphere, or Wernicke's area, provided the first evidence for a receptive language region in the brain. Damage to the posterior left hemisphere most frequently results in Wernicke's aphasia. Wernicke's aphasia is speech comprehension impairment with fluent but meaningless speech production.

Functional imaging studies using phonological or semantic decision tasks predominantly demonstrate activation within Wernicke's area, specifically the superior temporal sulcus and planum temporale (Binder et al., 1996; Pugh et al., 1996). The amount of activation is frequently greater in the left hemisphere than in the right hemisphere, supporting the finding that left hemisphere lesions more often produce oral comprehension deficits compared to right hemisphere lesions. These data suggest that neurons within the superior temporal sulcus and the planum may process higher order components of sounds, such as phonemes. Intraoperative mapping of receptive language prior to neurosurgery has shown that neurons within Wernicke's area are involved in processing speech sounds. But neurons responsive to speech are not restricted to Wernicke's area (Ojemann et al., 1988).

Animal models for receptive language

There is not an animal model of hemispheric localization for receptive language. However, hemispheric dominance for the recognition of species specific communication is found in Macaque monkeys and the house mouse. In these studies, ear advantage was taken as evidence for hemispheric dominance. Macaque monkeys showed a REA for discriminating among monaurally presented "coo" sounds for their own species (Petersen, 1978). And house mouse mothers did not respond to the ultrasonic calls of their offspring when the right ear was plugged, but did respond when only the left ear was plugged (Ehret, 1987).

The anatomy of receptive language

Wernicke's area includes the posterior superior temporal gyrus and supramarginal gyrus. Beginning at Heschl's gyrus, secondary auditory cortex extends posteriorly along the superior temporal gyrus and becomes the supramarginal gyrus. This secondary association cortex is called the planum temporale. The planum has a horizontal bank that is part of the superior temporal gyrus and a vertical bank that becomes the supramarginal gyrus. The planum constitutes the heart of Wernicke's area (see Figure 1). This area of the temporal lobe is thought to process speech sounds.

The planum temporale

In 1968 Geschwind and Levitsky examined the planum temporale, in 100 post-mortem adult brains. Sixty-five of the brains had a planum temporale that was larger on the left than the right or leftward asymmetry. Twenty-four brains demonstrated symmetry between the right and left plana size. Eleven brains exhibited a reversed or rightward asymmetry.

The distribution of planar asymmetry demonstrated by Geschwind and Levitsky has been replicated (LeMay, 1976). Leftward asymmetry of the planum has also been demonstrated in fetal and infant brains (Wada, 1977; Wada and Davis, 1977; Witelson and Pallie, 1973; Chi et al., 1977). These findings suggest that asymmetry of the planum temporale is present very early in life and may increase during childhood.

To determine if the left or right planum contributed more to the asymmetry, Galaburda examined the black and white photographs from Geschwind and Levitsky's 100 post-mortem brains. In comparison to brains with leftward asymmetry, symmetrical or rightward asymmetric plana exhibited a right planum that was increased in size. Most cases of symmetry were not due to a small left planum, but a larger right planum.

The development of MRI scanning of the brain has allowed for the measurement of brain structure in living subjects. MRI studies of planar asymmetry have replicated the post-mortem findings by showing a leftward asymmetry of the planum in the majority of samples drawn from the normal population (Steinmetz et al., 1991; Kulynych et al., 1995; Leonard et al. 1993; Leonard et al., 1998; Habib et al., 1995; Gauger et al. 1997).

One characteristic related to planar asymmetry is a non-specific effect of hand preference. Subjects who are non-right-handed (mixed and left handed) tend to exhibit less extreme leftward asymmetry of the planum (Habib, 1995; Pieniadz and Naeser, 1984; Foundas et al., 1995, 1992; Steinmetz et al., 1991). Although the difference in planar asymmetry between right and non-right-handed people is small, the effect is consistent. In addition, Steinmetz et al. (1991) reported that left-handed subjects with a family history of left hand preference were most likely to exhibit reversed asymmetry.

The Cytoarchitecture of the Planum. Auditory cortex has been categorized based on cytoarchitectonics, function, and gross anatomical structure. The planum temporale is one example of a region given multiple names that distinguish it as having a unique cytoarchitecture relative to surrounding brain region. The cytoarchitectural labels for the planum include TB, Tpt, and Brodmann area 22.

Areas TB, Tpt or 22 exhibit a greater density of pyramidal cells than primary auditory cortex (Zilles, 1990). From the anterior boundary with primary auditory cortex to posterior sections of the planum there is a continuous increase in columnar organization of pyramidal cells. Surprisingly, columnar organization is reported to be less pronounced in the right hemisphere (Seldon, 1981; Ong and Garey, 1990).

Hemispheric differences in the cytoarchitecture of the planum temporale are one probable explanation for planar asymmetry. Galaburda (1980) examined the differences in cytoarchitecture between the left and right planum in cadaver brains from the Yakovlev collection. The Tpt occupied the posterior lateral planum and appeared to contribute to the area producing planar asymmetry. The area of Tpt was then compared to the size of the planum. With decreasing leftward planar asymmetry the area of Tpt decreased minimally in the left hemisphere and increased in the right hemisphere until the areas were nearly equal in the two hemispheres. In summary, symmetry or rightward asymmetry was most frequently associated with a large right planum rather than small left planum, and leftward asymmetry was the result of a small right planum. Changes in asymmetry area could be attributed to changes in size of the right Tpt area.

Animal research supports the Galaburda (1980) finding. Rosen examined asymmetries in area 17 and somatosensory cortex of the rat (Rosen, 1996). In both areas, rats with asymmetry had one side that was smaller compared to rats with symmetric brains. The reduction in size was not related to cell packing density but the total number of neurons in the region.

Cerebral Asymmetry: Language Dominance and Performance

The hypothesis that cerebral asymmetries represent the functional lateralization of language has become a popular belief (Gannon, 1998). This hypothesis was driven by the observation that language deficits following a left hemisphere lesion are more likely to occur than following a right hemisphere lesion; and the discovery of leftward hemispheric asymmetry of the anatomical regions implicated in language deficits following lesions. However, there is limited evidence for anatomical correlates to language dominance.

The first study to examine the relationship of brain asymmetry to hemispheric speech representation used angiograms to infer sylvian fissure asymmetry and the WADA to infer hemispheric dominance for language (Ratcliff et al., 1980). The orientation of the middle cerebral artery creates an angle, related to sylvian fissure morphology, that can be measured on angiograms. The left hemisphere angle is typically sharper than the right hemisphere angle. Hemispheric difference in this angle was used as an index of temporal lobe asymmetry. The WADA results demonstrated that 39 subjects exhibited left hemisphere representation for language, 11 had bilateral representation, and 9 tested with a right hemisphere localization for language. The normal angle asymmetry between the vessels was found in patients with typical language representation. Atypical asymmetry was found only in patients with right hemisphere language representation.

Direct measures of cerebral asymmetry using MRI have revealed that anatomical asymmetry is related to hemispheric language localization in epilepsy patients. Atypical planum temporale and pars triangularis asymmetry were only seen in the one non-right-handed epilepsy patient with right hemisphere language representation. All other patients with left hemisphere language exhibited normal leftward asymmetry (Foundas et al., 1996).

WADA language dominance was also weakly predicted by occipital pole asymmetry in 55 epilepsy patients (Charles et al., 1997). The length of the left and right frontal, parietal, and occipital lobes were measured. Only the occipital lobe asymmetry exhibited a relationship to language dominance. Leftward occipital pole asymmetry was not predictive of left hemisphere language dominance. But rightward asymmetry of the occipital lobe length was present in 6 or 7 patients who were non-right- handed and had bilateral representation of language.

One explanation for the localization of language to the left hemisphere has been that the cytoarchitecture of the left hemisphere facilitates processing of discrete phonological stimuli that have rapid onsets and changes during voicing. The Seldon (1981) and Ong & Gary (1990) work suggest there are distinct differences in the columnar organization of the left and right plana. However, these studies are not definitive because of the small sample sizes.

Significance of size and asymmetry of the planum temporale

One assumption of structural neuroimaging studies is that the size of a brain region provides information about the information processing capabilities for the behavior that is believed to map onto that region. The size of the region represents the amount of resources available for processing that information Specifically, the surface area of a region is believed to increase as a function of the size of the receptive field of neurons that process task relevant information.

The receptive field assumption underlying structural imaging studies is drawn from neurophysiology research. Primary auditory cortex exhibits a tonotopic organization (Merzenich and Brugge, 1973). Frequencies are represented high to low from medial to lateral positions along primary auditory cortex. Disruption of primary auditory cortex by a tumor can produce ringing (Zatorre et al., 1988). But the role of primary auditory cortex in speech perception is not understood. The primate primary auditory cortex does show temporal patterns of activation that correspond with changes in voice onset time for stop consonant and vowel syllables (“ta” or “da”) (Steinschneider et al., 1993). However, functional imaging studies have yet to demonstrate activation in human primary auditory cortex that is specific for language.

Animal research shows that receptive fields can be altered following lesions or learning and reward (Merzenich et al., 1996; Nudo et al., 1996). There is also evidence that cortical maps in humans can be altered by experience. Karni et al. (1995) report an enhanced activation or representation for a sequential finger opposition motor task after three weeks of training. Tonotopic maps in auditory cortex (Merzenich and Brugge, 1973), retinotopic maps in visual cortex (Tootel et al., 1988; Sereno et al., 1995; Van Essen, 1994) and spatial maps in parietal and frontal cortex (Goldman-Rakic, 1988) suggest that cortical maps in primary sensory cortex are probably maintained in higher order sensory cortex. Early developmental experience could enlarge specific maps and alter the size of cortical regions subserving a particular sensory or cognitive function.

Schlaug et al. (1995) and Amunts et al. (1996) used this assumption to interpret their studies examining the relationship of neuroanatomical surface area to pitch identification accuracy ("perfect pitch") and the age at which musical training began, respectively. Schlaug showed that musicians with perfect pitch who began their musical training at an early age had an exaggerated left planar surface area compared to other musicians and non-musicians. Amunts found that the surface area of primary motor cortex was also larger on the left if music training began early in life. In both studies, the results suggest that cortical surface area can be used as a gross morphological index of receptive field changes induced early in life.

However, in both the Schlaug et al. (1995) and Amunts et al. (1996) studies there were no adequate anatomical or genetic controls. The asymmetry effect might not have been specific to motor cortex. An alternative conclusion for both studies is that individuals with perfect pitch and individuals who learn to play an instrument at an early age have brains that are organized and structured differently from less musical controls.

The receptive field assumption is concordant with the finding that left hemisphere language localization is associated with leftward asymmetry of the planum temporale (Foundas et al., 1995). Ninety-five percent of the population is estimated to have language localized to the left hemisphere (Annett, 1976). And 65% of the population have leftward planar asymmetry (Geschwind & Levitsky, 1965). Based on the receptive field hypothesis, a large left planum should be found in people with left hemisphere language because of the neural resources needed to perceive and comprehend speech .

There is evidence from birdsong studies to support this concept of receptive fields for language, or at least the idea that a certain amount of tissue must be dedicated to successfully process speech sounds. In song birds, the number of songs performed is not related to the size of the HVC (Brenowitz et al., 1995), although levels of testosterone and season of the year do influence HVC size (Grisham and Arnold, 1995; Gulledge and Deviche, 1997; Brenowitz et al., 1998). However, Ward, Nordeen and Nordeen (1998) have shown that the size of the HVC is significantly related to the accurate reproduction of syllables in a song learned from a adult male. Because song learning does not appear to influence the size of the HVC, the results are interpreted such that the size of the HVC constrains the amount of song material that can be accurately learned and/or reproduced.

When the planum was found to exhibit reversed asymmetry in subjects with language impairment the interpretation was that language failed to properly localize and that this led to language impairment (Galaburda et al., 1985). An alternate interpretation based on evidence from bird song suggests that reversed asymmetry constrains the amount of cortex available to process and store phonological units of information. This may be the correct interpretation for children with specific language impairment who have reversed asymmetry due to a small left hemisphere. However, most evidence relating planar asymmetry to phonological and verbal ability suggests that it is a large right hemisphere that is responsible for the relationship between anatomical asymmetry and phonological processing.

Anatomical correlates for language performance

Galaburda et al. (1985) was the first to report evidence of a neuroanatomical correlate for language function in a group of post-mortem brains. The brains Galaburda studied had belonged to a group of individuals with language impairment. Described as dyslexic, these language impaired subjects were a heterogeneous group that included individuals with developmental language delay, seizures, attention deficit, a speech production deficit, traumatic brain injury, psychiatric disturbances and included 3 people with a non-right- hand preference. Galaburda claimed the planum temporale was symmetrical or exhibited rightward asymmetry in all eight brains.

The original explanation for this finding proposed that slow growth in the left hemisphere could result in enlargement of cortical regions in other cortical regions, including homologous regions in the right hemisphere (Geschwind & Galaburda, 1985). However, this theory has been reformulated to be concordant with the finding that it is variability in the right planum, not a small left planum, that produces planar asymmetry or lack of asymmetry (Galaburda, 1990). The more recent theory proposes that failure to adequately prune the right hemisphere results in planar symmetry.

The Galaburda finding initiated a new research area designed to find the neuroanatomical basis for reading and language performance. A number of computerized assisted tomography (CAT) and MRI studies attempted to replicate the Galaburda finding in dyslexic and language impaired subjects. However, evidence for temporal lobe and planar symmetry or rightward asymmetry in dyslexic subjects has been inconsistent. The inconsistency is most likely due to the methodology and subjects definition. Atypical planar asymmetry is a consistent finding among subjects with oral language impairment. Both oral language-impaired and dyslexic subjects exhibit phonological deficits, but the reason for the different neuroanatomical relationships between the two groups could be due to another distinguishing characteristic, verbal IQ.

Plante et al . (1991) examined the asymmetry of a perisylvian measurement in a group of male children with language impairment[1]. Six of 8 (75%) of the language-impaired children exhibited symmetry or rightward asymmetry of the perisylvian area. The left to right ratio was significantly different from controls with leftward asymmetry. Reversed asymmetry was also found in the parents of the affected children. The probability of the parent having atypical perisylvian asymmetry was .86 when the parent reported a history of language problems (Plante, 1991)[2].

1.The perisylvian measurement included the planum temporale, some inferior frontal gyrus and primary motor and sensory cortex.

2. An effect of hand preference was not reported in the Plante (1991) study. 75% of the probands were reported to be right-handed. And only 3 family members of 3 right-handed probands were reported to be non-right-handed.

Plante's 1991 data replicated an earlier MRI study that demonstrated rightward asymmetry of the perisylvian region in a 4.9 year old boy who was receiving services for language impairment. Atypical asymmetry of the perisylvian area was also found in the boy's normal twin sister. Both children were reported to be right-handed (Plante et al., 1989).

Atypical neuroanatomical organization has also been demonstrated in language impaired children by Jernigan et al., (1991). The anatomy of 20 children with expressive and receptive deficits (13 males: 7 females) was compared to 12 controls (8 males: 4 females) using MRI. All subjects ranged in age from 8 to 10 years. The language impaired children had a higher incidence of reversed asymmetry in the parietal operculum (defined as the supero-posterior region). The LI children also had significantly less voxels in the left inferoposterior region (including the temporal lobe) and less inferoanterior voxels (inferior frontal cortex) than controls. Only 3 subjects were not right-handed. Excluding these subjects from the analyses reduced the effect sizes by only a small margin.

More recently, Gauger (1997) reported that symmetry or rightward asymmetry of the planum temporale and pars triangularis was more likely in children with specific langauge impairment. The brains of 11 children with language impairment (8 males: 3 females) were compared to 19 controls (14 males: 5 females). The average age of subjects in each group was 9.1 and 8.9 respectively. The language impaired children had bilaterally small plana and a small total brain volume (Gauger et al., 1997). The Gauger finding does differ from the Galaburda (1985) and Plante (1991) findings in which language impaired subjects had a larger right planum. However, all three studies used different measurement techniques, making interpretation of the differences difficult.

MRI findings of neuroanatomical differences between dyslexic and normal subjects

MRI has been used to compare dyslexic and normal subjects with the hope that gross neuroanatomical measures will distinguish normal readers from dyslexics. There is a great deal of inconsistency in the literature concerning the effect of reading group on the size and asymmetry of the planum temporale and the sylvian fissure. Table 1-2 presents the sample characteristics, methods and findings of these studies.

Much of the discrepancy is due to defining the population of dyslexics, the methods used, and the demographic characteristics of the dyslexic samples. For example, Hynd et al. (1990) reported dyslexics had significantly different planar asymmetry than control subjects. The dyslexics were more likely to have reversed asymmetry. However, the dyslexics were also more likely to have a left hand preference. Therefore, the group differences could have been due to a well documented hand preference effect on planar asymmetry rather than dyslexia. Two recent studies of well defined phonological dyslexics and their matched controls did not find group differences in planar asymmetry (Rumsey et al. 1997; Leonard et al., 1998). These studies used similar measurement methodology and imaging protocols.

The discrepant findings in the dyslexia literature and consistent findings in the language impairment literature suggest that the distinctions, not the commonalities between the two forms of linguistic impairment are related to planar asymmetry.

Table 1.2 A Comparison of Dyslexia Imaging Studies.

Authors	Rumsey et al., 1986	Hynd et al., 1990	Larsen et al., 1990	Duara et al., 1991	Kusch et al., 1993	Leonard et al., 1993	Schultz et al., 1994	Rumsey et al., 1997	Leonard et al., 1998
Subjects	10 M 18-28 yrs Hx RD	10 D 10 N	19 D 19 N	21 D 29 N **N not matched well on sex, age or educ.**	17 D 21 N	9 D 12 N	17 D 15 N	16 D 14 N	9 D 15 N
Hand Preference	All Strongly RH	**D 38% RH** **N 96% RH**	**No hand preference info.**	Edin. H. D .80 N .80	**Edin. H.** **D .63** **N .79**	All Subjects RH, except 1 relative	All Subjects consistent RH	All Subjects consistent RH	50% consistent RH
FSIQ	85-121	D 108 (9) N 109 (12)	Raven: D 42 (8) N 43 (6)	D 114 (5) N -------	D 104 (9) N 118 (12)	D ------- N -------	D 117 (11) N 121 (14)	D 111 N 113	BCA: D 10 N 10

Authors	Rumsey et al., 1986	Hynd et al., 1990	Larsen et al., 1990	Duara et al., 1991	Kusch et al., 1993	Leonard et al., 1993	Schultz et al., 1994	Rumsey et al., 1997	Leonard et al., 1998
MR Protocol	**.5 Tesla, 10 mm thick axial sections**	**.6 Tesla, 5 mm thick sagittal sections; 1 section measured**	1.5 Tesla, 3 mm thick coronal sections	1.5 Tesla, **7 mm thick axial sections**	1.5 Tesla, **5 mm thick axial sections**	1 Tesla, 1.25 mm thick sagittal sections	1.5 Tesla, 5 mm thick coronal sections	1.5 Tesla, 1.5 mm thick sagittal section	3 Tesla, 1 mm thick sagittal sections
Finding	9/10 D had temporal lobe symmetry on **clinical evaluation**	10% D had leftward planar asymmetry due to smaller left planum	D greater frequency of planar symmetry due to larger right planum	outline of mid-posterior section (including somatosensory cortex) showed rightward asymmetry in D and leftward asymmetry in NC	anterior and posterior surface halves of superior temporal lobe symmetric in D and leftward asymmetry in NC	No main effect of diagnosis	No main effect of diagnosis	No main effect of diagnosis	No main effect of diagnosis

D-Dyslexic, N-Normal Control; FSIQ-Full Scale IQ; RH-Right-Hand Preference; Edin.-Edinburgh Handedness Questionnaire; M-Male The confounds of studies showing a difference in Dyslexic and Control anatomy are highlighted in bold. BCA-Woodcock-Johnson Broad Cognitive Assessment.

Language-impaired individuals experience both oral and written language problems compared to dyslexics who experience only written language deficits.

Planar Asymmetry and Normal Language Performance

Variability in planar asymmetry between language-impaired and control subjects suggest that the planum is related to language functioning, specifically oral language competence. The differences between language-impaired and normal subjects might also represent the extremes of language ability or anatomical structure at the ends of normal distributions. Normal subjects with varying phonological and verbal skills have shown linear relationships between those skills and planar asymmetry.

The Rumsey et al. (1997) study failed to show a difference between dyslexics and controls. However, they did report significant relationships between planar asymmetry and 4 of 6 phonological measures (they did not report which tasks were significant) and a measure of verbal IQ among the control subjects. Control subjects with a right-hand preference had better phonological and verbal skills if they had a left planum that was larger than the right planum. Phonological and verbal skills declined as the right planum size increased.

A similar relationship in a sample of children has been previously reported (Leonard et al., 1996). The phonemic awareness of 40 children between 6 and 13 years of age was significantly predicted by planar asymmetry. The data exhibited a nonlinear slope perhaps because of ceiling effects among the older children. Therefore, the neuroanatomical relationship with phonemic awareness was slightly obscured by age. A trend for the right planum size to decrease with age was also found in this cross sectional sample. Although the planum predicted phonemic awareness, it is not clear as to whether phonological skills develop with a decreasing planum across time or there was simply an age confound.

The Rumsey et al. (1997) and Leonard et al. (1996) provide evidence that the planum temporale predicts phonological and verbal skills in normal right-handed adults and children. However, the Leonard et al. (1996) study needs to be replicated. Studies attempting to find neuroanatomical markers for reading and language performance have shown mixed results that may be attributed to methodological differences. Nonetheless, the prevailing conclusion from neuroimaging studies is that planar asymmetry is related to hand preference and oral language skills.

Nature & Nurture Models for Reading Development

The preceding review of the literature suggests that there are both environmental and biological effects on language and reading development. The nature versus nurture debate continues in some academic areas, and primarily for political reasons. Nature and nurture interactions are frequently discussed and accepted as the norm among geneticists and animal researchers. However, only recently has epigenesis begun to be discussed and accepted with regard to language and human subjects.

One reason for the reluctance to depart from nature versus nurture arguments is the politically uncomfortable question of whether there are genetic differences among racial or income groups. The different distribution of racial groups in socioeconomic environments confounds an understanding of epigenetic effects and leaves results open for the interpretation that race also matters. The Bell Curve, by Hernstein and Murray (1994), reported that IQ varies according to ethnic groups. The negative reaction to The Bell Curve is an example of why researchers shy away from examining questions related to race. At the heart of any trepidation over the race issue is the possibility that this type of research could influence equal opportunity and in particular legal equality (Weyher, 1998).

Interactions. There are many animal studies that exemplify gene and environmental interactions on the developing organism. One example of epigenetic effects is the development of claw asymmetry in lobsters. Lobsters have a large crushing claw and a thinner cutting claw that appear with equal probability to the left or right side of the body (Govind and Potter, 1987). The claws also differ with respect to muscle fiber types. Crusher claws have slow muscle fibers and cutter claws have fast muscle fiber types. However, early in development there is no difference in claw type or muscle fibers. During a sensitive period in development the claws differentiate. Inhibiting nerve activity to a claw prevents crusher claw development. Eliciting reflex activity in the claw promotes development of the crusher type. However, bilateral reflex exercise does not produce a crusher claw. The development of a cutter or crusher claw depends on asymmetry in the amount of activity between the two claws. The more active claw becomes the crusher claw. Experience with the environment is probably a critical mediating factor during the sensitive developmental period that influences which claw is more active.

Human development also shows that environmental stimuli during genetically determined sensitive periods can influence development. For example, at birth infants can detect phonemes from any language in the world. But by two years of age they have established sound boundaries for categorizing the range for native speech sounds and fail to detect phonemes that are unique to other languages (Kuhl, 1992).

Second language learning is another example. There is a linear relationship between the success of second language acquisition and age prior to puberty. After puberty, language learning is more difficult and there is no relationship between language learning success and age (Johnson and Newport, 1989). These human studies parallel results from birdsong learning in which the environment interacts with the timing of neural development to influence song learning. There is a critical period in avian development in which model songs are perceived, practiced and crystalized in memory. Each example, human and animal, demonstrates an efficient nervous system that is responsive to an animal's environment to promote fitness in that environment.

Main Effects. This review of the nature and nurture relationship to development has focused on interactions. But genes and the environment can have independent effects. Human twin studies are examples of studies examining the independent contributions of genetics or environment to behavior.

Dale et al. (1998) examined the main effects of heredity and environment on language development in more than 3000 pairs of two-year-old twins. One of the goals of the study was to determine if language impaired children are a clinically distinct group, or are just at the low end of the continuum for language learning. The children were ranked and placed into percentile performance groupings using parental report of vocabulary size as an index of language development. Vocabulary size of children from the tenth percentile to the hundredth percentile was strongly influenced by the shared environment of the twins (approximately 60% of the variance) and moderately by heredity (approximately 30% of the variance). However, for language-delayed children in the bottom fifth percentile, nearly 70% of the variance in vocabulary size was accounted for by heredity. The authors conclude that the strength of heredity or environment for predicting language development was different depending on whether language delay or individual differences in development were examined (although the question is whether any performance above the fifth percentile constitutes language delay). It should also be noted that it is not possible to extract parental genetic contributions to the children's developmental environment.

Unfortunately, there are no neuroimaging studies of language and reading development or performance that attempt to account for environmental effects. One reason is that most samples in neuroimaging studies come from university communities. Although Elena Plante has studied low income subjects, they were severely language-impaired and probably fall into the Dale et al. (1998) bottom fifth percentile. One important message from the Dale et al. (1998) study is that any imaging study examining individual differences in language or reading must include assessment of environmental variables.

Dissertation Goals.

The purpose of this study was to 1) replicate the Leonard et al. (1996) finding in a group of same age, right and non-right-handed children from the public school system; 2) determine if neuroanatomy predicts the rate of reading skill development; 3) address exploratory hypotheses regarding the relationship of frontal lobe neuroanatomy to language production. These goals were examined in a quasi-epidemiological sample of 39 6th grade children from the Alachua County, FL public school system. This is a unique sample because the subjects were tested in kindergarten, 1st grade and 6th grade for their phonological skills and reading comprehension. During the 6th grade phase of the study the children also received an MRI scan that was used to measure neuroanatomical structures and test a number of hypotheses regarding the relationship of brain structure to phonological skill and reading success. Based on the preceding literature review, tables 1-3 through 1-7 present the proposed hypotheses along with potential outcomes of the hypotheses. For each of the hypotheses, environmental factors were anticipated to make additive contributions in predicting reading skill.

Table 1-3 Hypothesis 1.

Leftward asymmetry of the planum temporale will be positively related to Kindergarten pre-reading skills.

Possible Outcomes:

1. Planar asymmetry predicts pre-reading skill.
2. Planar asymmetry does not predict pre-reading skill.
3. Planar asymmetry uniquely predicts pre-reading skills.
4. Planar asymmetry does not uniquely predict pre-reading skills from other anatomical measures.

Table 1-4 Hypothesis 2 & 3.

Leftward asymmetry of the planum temporale will be positively related to reading skills in 1st grade and 6th grade, respectively.

Possible Outcomes:

1. Planar asymmetry predicts reading skills 1st grade, 6th grade or both time points.
2. Planar asymmetry does not predict reading skills in 1st and 6th grade.
3. Planar asymmetry uniquely predicts reading skills.
4. Planar asymmetry does not uniquely predict reading skills when compared with other anatomical measures.

Table 1-5 Hypothesis 4.

Children having the greatest gains in reading performance, between 1st grade and 6th grade, will demonstrate a leftward asymmetry of the planum temporale.

Possible Outcomes:

1. Planar asymmetry predicts rate of reading development.
2. Planar asymmetry does not predict the rate of reading development.

Table 1-6 Hypothesis 5.

Children that continue to lag behind their peers in reading will have symmetrical plana.

Potential Outcomes:

1. Significant difference between groups suggests that planar asymmetry differentiates children who develop normal reading skills from those with below normal reading skills across development.
2. Non-significant effect of planar asymmetry would suggest that planar asymmetry is not a marker for children who will perform below their peers throughout development, or that handedness and/or SES is confounding the effect.

Table 1-7 Hypothesis 6.

Phase 3 speech production and naming skills will predict pars triangularis asymmetry.

Potential Outcomes:

1. Speech production and naming skills account for the same significant variance in PT asymmetry.
2. Speech production and naming skills each account for a unique amount of variance in PT asymmetry.
3. Non-significant effects would suggest that there is no effect, interactions with sex and handedness, the heterogeneous composition of the sample, or environmental factors obscuring an underlying biological relationship, or a restricted range in the variables.

CHAPTER 2
METHODOLOGY

The purpose of this longitudinal study was to determine if neuroanatomical structure predicts children's reading skill in kindergarten, 1st grade and 6th grade. This study involves 3 phases of behavioral testing and neuroimaging in the last phase of the project. This section describes the project time line, sample characteristics in each of the 3 phases, behavioral assessment tools, MRI protocol, brain measurement techniques, and statistical analyses.

Project Time Line

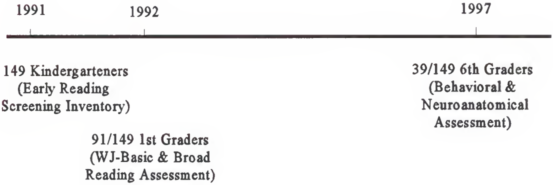

1991
1992
1997
149 Kindergarteners (Early Reading Screening Inventory)
91/149 1st Graders (WJ-Basic & Broad Reading Assessment)
39/149 6th Graders (Behavioral & Neuroanatomical Assessment)

Figure 2-1. Project Timeline

Participants

Recruitment

The participants in this study were recruited from the Alachua County, Fl. public school system. In Phase I of the study, 400 permission forms for participation in a longitudinal reading study were sent to the homes of children in 17 kindergarten classes, across 5 elementary schools. The 5 schools were selected because the research division of the Alachua County school system had determined they provided the most representative sample of families relative to socioeconomic status. Two hundred and sixteen forms (54%) were returned. Assessment time demands limited the sample to 149 children. These children were randomly selected from sex, race and achievement categories created from the 216 returned forms to provide a representation of the country. There were 69 males (46%) and 80 females (54%) ranging in age from 66-80 months. The group was composed of 104 Caucasian (74%), 42 African-American (28%), and 3 Asian-American children.

Phase II of the study occurred one year later. The 149 subjects were sent information and consent forms in the mail. Ninety one of the 149 children returned consent forms and participated in Phase II.

In 1997 the Alachua County School Board, Division of Research provided access to the names, addresses, and phone numbers of the children from Phase I who were still enrolled in the public school system. Eighty-eight children from Phase I remained in the public school system. This suggests that between 1991 and 1997, approximately 61 children either moved away from the area or were educated in the home or by private schools.

Letters providing information regarding Phase III of the study were sent to the 88 families of children who remained in the Alachua County public school system (see Appendix A). Each of the families was called to determine interest in the study. Upon obtaining verbal consent, 39 children were scheduled for behavioral testing and an MRI scan. Prior to behavioral testing, informed consent/assent was obtained from the children and parents.

Forty-nine children declined participation. Table 2-1 presents the reasons given for not participating in the study. Table 2-2 presents the demographic characteristics of the children from each explanation group. The majority of the families who originally agreed to participate but could not be scheduled and families that could not be contacted were families that qualified for lunch subsidy. The majority of the families who declined to participate and gave no specific reason or who were worried about the MRI scan were families of children placed in gifted programs and were not receiving lunch subsidy (Appendix B provides the 1997-1998 federally defined scale for receiving lunch subsidy for a family of 1 and a family of 8).

Table 2-1. Explanations for Non-Participation Among the 49 Children Remaining in Alachua County.

Reason for Not Participating	Number of Lost Subjects
Not interested without explanation	14
Agreed to participate but could not schedule after numerous attempts	9
Not reached after numerous attempts	8
Worried about the MRI scan	5
Braces (MRI exclusionary criterion)	3
Too many medical experiences	2
Death in the family	1
Didn't see any good for the child	1
Withdrew from study without explanation	1
Unknown	5
TOTAL	49

Table 2-2. Demographic Characteristics of Children Who Did Not Participate by Type of Explanation.

Reason for Not Participating	Receiving Lunch Subsidy	AA:C	M:F	ESE S&L	ESE Gifted	No ESE Services
Not interested without explanation	3/16	4:12	8:8	1/16	7/16	8/16
Agreed to participate but could not schedule after numerous attempts	7/9	7:2	1:8	3/9	2/9	4/9
Were never reached after numerous attempts	6/8	5:3	1:7	0/8	2/8	6/8
Were worried about the MRI scan	0/5	1:4	3:2	0/5	4/5	1/5
Braces (MRI exclusionary criterion)	0/3	0:3	1:2	0/3	2/3	1/3
Other (includes all other explanations from Table 2-1)	2/5	2:3	3:2	1/5	0/5	4/5

C-Caucasian : AA-African American;
M-Male; F-Female;
ESE- Alachua County Public Schools Exceptional Student Education program;
S&L-Speech & Language Classes;
:-indicates comparison of numbers of subjects in groups
/-indicates a ratio of students in a category

Table 2-3. Sample Characteristics Across the Three Phases of this Project.

	Age Range (months)	Sample Size	Sex Ratio (Male:Female)	Ethnic Composition C:AA:AsA
Phase I	66-80	149	69(46%):80(54%)	104(70%):42(28%):3(2%)
Phase II	78-92	91	38(42%):53(58%)	66(73%):25(27%):0(0%)
Phase III	130-144	39	19(49%):20(51%)	28(72%):11(28%):0(0%)

C-Caucasian : AA-African American : AsA-Asian-American

The 39 phase III participants were representative of children from Phase I who did not participate in Phase III and of all 6th graders in the Alachua County public school system. The distributions of race (Pearson chi-square $_{(df=2)}$=4.90, ns), sex (Pearson chi-square $_{(df=2)}$ =2.90, ns), lunch subsidy (Pearson chi-square $_{(df=8)}$=2.85, ns) were approximately equal across the three phases of the study. In addition, there were no significant differences on an index of scholastic achievement (Iowa Tests of Basic Skills Total Score, $F_{(1,354)}$ =2.10, ns) between Phase III participants and of all 6th graders in the Alachua County public school system.

The sample included 27 children with a right-hand preference and 12 children with a non-right-hand preference. Hand preference was established using a quantitative handedness questionnaire (see below). A non-right-hand preference included children who scored below .75 on the handedness questionnaire. This cutoff is used because it was previously reported to be sensitive to differences in brain structure (Eckert et al., 1997). Birth difficulties for the non-right-handed children included cesarean section due to high blood pressure and low heart rate, fetal stress during labor, and 7 minutes of oxygen deprivation at birth. Birth difficulties for the RH children included fetal distress leading to an emergency C-section, the need for oxygen at birth, C-section due to the presence of herpes, jaundice and prolonged labor due to gestational diabetes, decreased heart rate after a long labor, and excessively high heart rate that lasted for a day.

Behavioral Assessment

Phase I

Phase I involved an assessment of basic reading skills using the Early Reading Screening Inventory (ERSI). The ERSI has four subtests that include Alphabet Knowledge, Concept of Word, Invented Spelling, and Word Recognition. Alphabet Knowledge tests a child's ability to name visually presented upper and lower case letters and write the letters when they are presented orally. Concept of Word requires a child to identify a word in the context of a story. Invented Spelling assesses a child's ability to spell 12 words that contain 3 or 4 phonemes. Word Recognition tests a child's ability to read 20 irregular and regularly spelled consonant-vowel-consonant words. Each of the scores on the 4 subtests are combined to provide a single index of reading skill. The maximum score for the total ERSI is 40. ERSI spelling was used as the kindergarten phonological variable because it was the most normally distributed ERSI variable. Spelling does significantly correlate with the other ERSI variables.

Phase II

In phase II, reading skill and performance was assessed with the Woodcock-Johnson Tests of Achievement. The Word Attack, Word Identification, and Passage Comprehension subtests were administered. Word Attack assesses phonetic skills by requiring pronunciation of words that are not real words and therefore not recognizable by sight. Word Identification assesses the participant's ability to name isolated real words. The words range in difficulty from that of a beginning reader to a level expected from adult readers. Passage Comprehension tests a subject's ability to understand a short reading passage and fill in a key word that is missing from the sentence. Raw scores on each subtest are converted to standard scores that are based on subjects expected performance for their age.

Phase III

Reading

Reading skill and performance were assessed a second time with the Woodcock-Johnson Word Attack, Word Identification, and Passage Comprehension subtests.

Phonological Processing

Reading skills falling under the umbrella of phonological processing skills were assessed. Phonological awareness was assessed with Torgesson's Phoneme Reversal. Phoneme reversal requires child to listen to a non-word, reverse the order of the sounds in the non-word, and orally produce the reversed order of the non-word to create a real word. Phonemic awareness was assessed using the Lindamood Auditory

Conceptualization Test (LACT). The LACT requires children to represent represent phonemes in simple and complex nonsense syllables with combinations of colored blocks. The Woodcock-Johnson Word Attack and Word Identification sub-tests are also considered indices of phonological awareness.

Phonetic recoding in working memory was tested using the Memory for Digits test (Torgesson). Memory for Digits requires the participant to listen to a series of numbers, ranging from 2 to 9 digits, and repeat the digits in the exact order in which they were presented. The argument can be made that both the LACT and Phoneme Reversal are both phonological awareness and phonetic recoding working memory tasks.

Phonological recoding in lexical access was assessed with the Rapid Automatic Naming task (RAN). Speed of naming is assessed with the RAN. On a laminated 8" x 10" card is a series of colors, uppercase letters, or numbers that a child must name as quickly as possible. The amount of time to name all the stimuli on each card is the naming speed for the particular stimulus on the

IQ

A short form of the Wechsler Intelligence Scale for Children (3rd edition) was used to provide an index of measured intelligence. The short form included the Information, Similarities and Block Design subtests. Information tests children's basic knowledge of the world. Similarities asks children to state the common characteristic of two orally presented words. The Block Design subtest requires the child to use red and white blocks to represent a two-dimensional design presented to them from a booklet. This short form was chosen to minimize the verbal weighting of IQ, but still maintain a high relationship to full scale IQ (reliability coefficient, r=.934; validity coefficient, r=.874) and *g*.

Handedness

Hand Preference was assessed using the a quantitative handedness questionnaire (Briggs & Nebes, 1974). The questionnaire has twelve items for which the subject states the frequency with which they perform a task (like throwing a ball) with their preferred hand. Hand motor skill was assessed using the Purdue Peg Board. A participant places pegs in holes with one hand as quickly as possible. Grip strength was determined with the Hand Dynamometer. Both hands are tested for motor skill and grip strength.

Hearing screening

The hearing thresholds of each participant were tested to rule out any potential hearing deficits. Children's detection of tones was tested at a threshold of 30db for 1000hz, 2000hz, 3000hz, 4000hz. The participant raised their left or right hand to signal they had heard the tone. All subjects passed the screening.

MRI Protocol and Measurement Methods

MRI Acquisition

Volumetric, gap-less, 1.25 mm thick images were acquired with a 1.5 T Seimens Magnetom Magnet using a MP-Rage protocol. Scan parameters were: a repetition time of 10ms; an echo time of 4 ms; flip angle of 10 degrees; a 25 cm field of view; and a 130 x

256 matrix. The images were transferred to Sun Microsystems workstations and reformatted into 1 mm thick sections to correct for tip in the coronal, axial, and sagittal planes of section. For each plane of section parameter files were created that contain the distance between the anterior commissure and borders of the brain. Talairach coordinates were used to normalize the location of brain regions across the sample of brains. Talairach coordinates allow the use of the same numbered reference system to identify similar locations among brains of different sizes. This procedure involves dividing the actual location in mm. by a Talairach factor obtained from the Talairach & Tourneaux Brain Atlas. The Talairach coordinate system corrects for brain size without warping or distorting the brain.

Quantification of Brain Structure

Surface area measurements were obtained for the planum temporale, pars triangularis, central and the olfactory sulcus. Total brain volume was also quantified for each subject. Measurement of the above structures was performed using programs written in PV-Wave (Visual Numerics, Boulder, CO.).

Surface areas were measured by manually tracing the structure with a mouse-operated cursor. Structures were measured on each 1 mm thick section between two Talairach coordinates that designated the structure boundaries. The total surface area was calculated by multiplying each section measurement by the section thickness and summing across all sections. A hemispheric asymmetry measure was obtained for each structure using the following formula: (L-R)/((L+R)/2). Images were magnified by a factor of 4 to provide easier visual identification of the structures of interest. Table 2-3 presents the intra-rater and inter-rater reliability for each measurement.

Planum temporale

The planum temporale forms the vertical bank and part of the horizontal bank of the sylvian fissure. The horizontal bank (PHR) extends from Heschl's sulcus to the origin of the vertical bank or posterior ascending ramus (PAR). The PAR, also called the planum parietal, rises from the termination of the PHR into the parietal cortex. The planum temporale can also have a descending ramus (PDR) that has its origin at the termination of the PHR. The surface area of the planum temporale (PHR, PAR, and PDR) was measured between 46-56 cm in medial to lateral sagittal sections. This is a measurement of the lateral portion of the planum temporale that was designed to emphasize hemispheric differences in the structure. Asymmetry of the planum is most dramatic in the lateral region of the planum temporale. These coordinates were also chosen in order to replicate the methods of previous MRI studies showing functional relationship to the asymmetry of the planum (Gauger et al., 1997; Leonard et al., 1996).

Pars Triangularis & Pars Opercularis

Pars triangularis (PT) is a frontal lobe structure lying within the inferior frontal gyrus or Broca's area and corresponds to Brodmann's area 45. The boundaries of PT are formed by the vertical and horizontal branches of the lateral fissure. The vertical branch of the lateral fissure forms the anterior boundary for pars opercularis (PO). The posterior boundary of PO is formed by the precentral sulcus. A combined surface area measurement of the PT and PO, the inferior frontal gyrus (IFG), was obtained in sagittal sections from Talairach coordinate 30 to coordinate 49. The coordinate boundaries for IFG were based on regions of activation during functional imaging tasks. Word generation tasks produce activation in the IFG between medial to lateral Talairach coordinates 30 to 49 (see Table 1-2).

Central sulcus

The central sulcus (CS) separates the frontal from the parietal lobe. It forms the most prominent fissure that is oriented perpendicular to the sylvian fissure. Surface area measurements of the CS were made in sagittal sections in the region that includes the "hand bump" (Penfield & Boldrey, 1937; Kim et al., 1993; Zilles et al., 1997). The boundaries for this region were Talairach coordinates 32 to 55 mm. The anterior bank of the CS was measured from the base of the CS to the peak of the posterior segment of the precentral gyrus. The posterior bank of the CS was measured from the base of the CS to the peak of the anterior segment to the postcentral gyrus. The central sulcus measurement was designed as a control region for any significant structure-function relationships involving the planum temporale.

Olfactory sulcus

The olfactory sulcus (OS) forms the lateral boundary of the gyrus rectus or straight gyrus. The OS is most easily identified in axial sections. The length of the sulcus was measured on each dorsal to ventral axial section in which the sulcus was easily visible and bounded by white matter. The average dorsal to ventral boundary was from Talairach coordinates. 80-100 mm. The olfactory sulcus measurement was used as a frontal control measure for any IFG effect with the speech production tasks.

Brain volume

Brain volume included the telencephalon (cerebral hemispheres) and diencephalon (thalamus and hypothalamus). The mesencephalon (midbrain), metencephalon (pons and cerebellum), and myelencephalon (medulla) structures were excluded from the measurement. A volume was obtained by tracing the brain from a midline sagittal section to the lateral edge of the brain on every fourth section.

Table 2-4. Intra-rater and Inter-rater Reliability for Neuroanatomical Measurements.

Structural Asymmetry	Intra-rater Reliability	Inter-rater Reliability
Planum Temporale		
Horizontal Ramus	.98	.86
Ascending Ramus	.94	.92
Pars Triangularis & Pars Opercularis	.88	.84
Central Sulcus		
Motor Bank	.90	.82
Sensory Bank	.91	.89
Olfactory Sulcus:	.97	.94
Total Brain Volume:	.98	.99

Statistical Analysis

Multiple regression and analysis of covariance (ANCOVA) was used to test the hypotheses outlined in chapter 1. A multiple regression and correlation power analysis was performed for a beta=.80 at alpha=.05. The relationship of planar asymmetry to phonological awareness in a previous study by Leonard (1996) was .42, $p<01$. This was the effect size used to determine the necessary sample size for 5 independent variables. The following formula was used to calculate the proper sample size: $f^2=r^2/1-r^2$ and $N=(L/f^2)+k+1$. The result of the power analysis $(N=(12.83/.2142) + 5 +1)$ suggested 66 subjects were needed for a beta of .80 at alpha=.05. Because of constraints on the sample selection (see recruitment above), it was not possible to reach a sample size of 66. The possibility exists that non-significant effects in the results section are the result of inadequate power to detect small or moderate but significant effects.

CHAPTER 3
RESULTS

This project was designed to examine the predictive power of structural asymmetry on basic reading skills across 3 time points during the elementary school years. Thirty-nine children (males, 19; females, 20; age range in years: Phase I: 5.5-6.7; Phase II: 6.5-8.3; Phase III: 10.8-12) from an original Phase I sample of 149, participated in this study. The reading skills of these subjects were tested during phase I, Phase II, and phase III. During Phase III additional tests of handedness, digit span memory, naming performance, and IQ were given. An MRI scan was used to obtain quantitative measurements of the planum temporale, inferior frontal gyrus, olfactory sulcus, central sulcus and whole brain volume of each subject. These data were collected to address the hypotheses outlined in chapter one.

An initial inspection of the data suggested that hand preference interacted with the SES, behavioral and neuroanatomical variables. Analyses were performed for the entire sample and according to hand preference when appropriate. Descriptive statistics and simple correlations of the behavioral data for each phase of the study and for the neuroanatomical data can be found in Appendices B. Significant correlation paths of the behavioral data are presented in the first section of this chapter. Effects of SES are analyzed in the next section. Univariate analyses of the neuroanatomical asymmetry measures are then presented. The last portion of this chapter includes tests of each hypothesis with the appropriate post-hoc analyses, and significant demographic and neuroanatomical influences on the data. Table 3-19 presents a brief summary of the results for each hypothesis.

Path Presentation of Significant Behavioral Correlations

Figure 3-1 presents a visual display of the relationships among all of the behavioral variables. Significant paths are presented with respect to time, in which only the earlier phases are predicting later phases of the study. Relationships among the phase 2 and phase 3 variables are those that are significant after the effects of Kindergarten ERSI-Spelling have been removed. This was done because ERSI-Spelling was such a dominant predictor of the phase 2 and 3 variables and it was of interest to examine these relationships without the effects of ERSI-spelling. The behavioral variables are highly interrelated across every phase of the study. However, Naming speed demonstrated weak associations with other behavioral measures.

Socioeconomic Status (SES)

SES was a strong predictor of behavioral performance at each phase of this study. The effect of SES on reading skills is apparent in the hypothesis testing section of this chapter (see Appendix B). SES also predicted other demographic and parental involvement variables. Children from families with a higher income have parents with

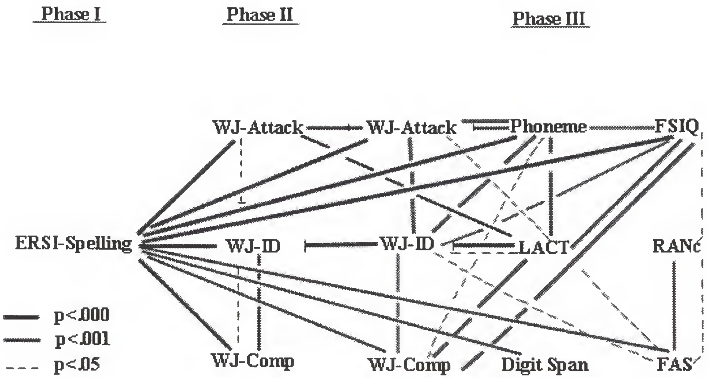


Figure 3-1. Behavioral Relationships

more years of formal education (father, F=13.75, p<.001; mother, F=16.02, p<.001), homes in which there is exposure to more books (Children's books, F=8.16, p<.01; Adult books, F=6.04, p<.05) and in which there is more parental time investment in the children's homework activities (F=4.46, p<.05). Figure 3-2 presents the distribution of parental homework help by lunch status.

As strong as SES was in predicting behavior, it was equally weak in predicting any of the neuroanatomical variables. Only 1 of 22 neuroanatomical variables was significantly different between the two lunch status groups. Right-handed children not receiving lunch subsidy had a significantly larger right inferior frontal gyrus surface area than right-handed children receiving lunch subsidy. However, there is a strong probability that this effect was due to chance. After correction for multiple comparisons, the effect was not significant.

Neuroanatomical Hemispheric Asymmetries

Hand preference is a strong predictor in anatomical asymmetries. Univariate analyses were performed to determine if the coefficient of asymmetry for each neuroanatomical variable was significantly different from zero. Results of these analyses are presented for all 39 subjects and by hand preference groups in tables 3-1 to 3-3.

Table 3-1 demonstrates that the olfactory sulcus and ascending ramus of the planum temporale exhibit significant rightward asymmetries at the .05 alpha level. The horizontal ramus of the planum temporale displays the strongest hemispheric asymmetry.

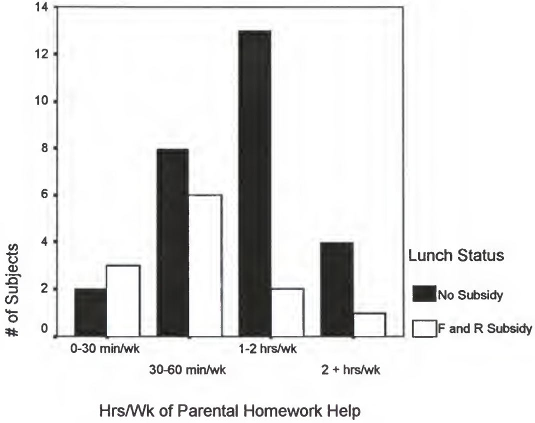


Figure 3-2. Lunch Status Predicts Homework Help

Table 3-1. Hemispheric Asymmetry of the Neuroanatomical Variables.

Structural Asymmetry	t	df	p value (two-tailed)
OSA	**-2.382**	**37**	**.022**
IFGA	1.064	38	.294
MBA	-0.215	38	.831
SBA	0.653	38	.518
PARA	**-2.076**	**38**	**.045**
PHRA	**3.965**	**38**	**.000**

OSA-Olfactory Sulcus Asymmetry
IFGA-Inferior Frontal Gyrus Asymmetry
MBA-Motor Bank Asymmetry
SBA-Sensory Bank Asymmetry
PARA-Planum Temporale, Ascending Ramus
PHRA-Planum Temporale, Horizontal Ramus

Tables 3-2 and 3-3 demonstrate that children with a right-hand preference exhibit significant rightward asymmetry of the olfactory sulcus that was not present in children expressing a non-right-hand preference. Examination of table 3-2 reveals that the significant PARA in table 3-1 was a weak effect that was dependent on an adequate sample size to reach significance. Neither hand preference group exhibits a significant PARA. Finally, while both hand preference groups exhibit a significant leftward PHRA, this effect was most pronounced in the right-hand preference group. However, there was not a significant difference in the PHRA asymmetry of the two groups ($F_{(1,38)}$=.177, ns). The difference in univariate p-values is most likely due to sample sizes in each group.

Table 3-2. Hemispheric Asymmetry of Neuroanatomical Variables in Right-Handed Children.

Structural Asymmetry	t	df	p value (two tailed)
OSA	**-3.470**	**23**	**.002**
IFGA	1.194	26	.243
MBA	0.818	26	.421
SBA	0.440	26	.664
PARA	-1.593	26	.123
PHRA	**2.981**	**26**	**.006**

Table 3-3. Hemispheric Asymmetry of Neuroanatomical Variables in Non-Right-Handed Children.

Structural Asymmetry	t	df	p value (two tailed)
OSA	0.307	11	.765
IFGA	0.227	11	.825
MBA	0.841	11	.418
SBA	0.485	11	.637
PARA	-1.344	11	.206
PHRA	**2.631**	**11**	**.023**

Hypothesis Testing

Hypothesis 1

Leftward asymmetry of the planum temporale was predicted to be positively related to pre-reading skills. Multiple regression analysis was used to determine if planar asymmetry was uniquely related to ERSI spelling performance. Neither PHRA or IFGA asymmetry predicted kindergarten spelling performance. However, motor bank asymmetry did predict a significant and unique amount of variance in spelling performance. Table 3-4 to 3-5 present the results of this analysis.

When the significant relationship between motor bank asymmetry and ERSI-spelling was examined by hand preference and SES, it was apparent that this relationship was driven by right-handed children who do not qualify for subsidized lunch (r=.697, p=.002). Figure 3-3 presents the influence of SES on ERSI-spelling. There was not a significant relationship between motor bank asymmetry and ERSI-spelling for the other hand preference and SES groups (see Figure 3-4).

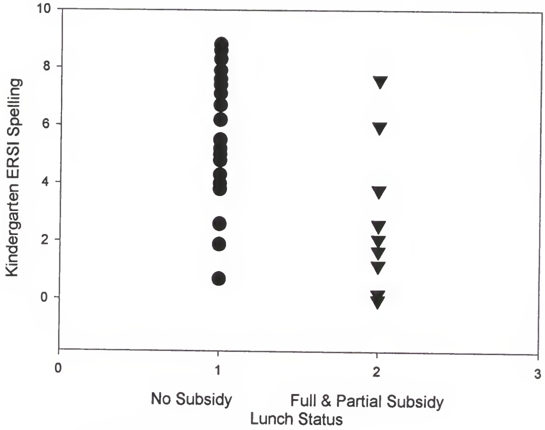
The relationship of MBA to Spelling in right-handed children without lunch subsidy is dependent on both the left and right motor bank surface areas. A stepwise regression of Spelling using MBA, left motor bank and right motor bank as predictor variables demonstrated that MBA was the only variable to be entered in the model (Std. B=.687, p=.002). An examination of the simple correlations shows that only MBA is significant with Spelling at the .05 alpha level. However, the left motor bank surface area does approach significance (.418, p=.095) while the right motor bank is non-significant

Table 3-4. Multiple Regression Model Results for Hypothesis 1.

MODEL R	R	R-Square	Adj. R-Square	Std. Error of the Estimate	F	Sig.
PHRA	.133	.018	-.009	2.97	0.67	.420
PHRA, MBA	.383	.147	.099	2.80	3.09	.058
PHRA, MBA, IFGA	.427	.183	.113	2.78	2.61	.067
PHRA, MBA, IFGA, Lunch Status	**.640**	**.410**	**.341**	**2.40**	**5.91**	**.001**

Table 3-5. Multiple Regression Coefficients for Hypothesis 1.

Model	Variables	B	Std. error	Std. B	t	Sig.
1	(Constant)	4.42	0.57		7.83	.000
	PHRA	.68	0.84	.13	.816	.420
2	(Constant)	4.58	0.54		8.52	.000
	PHRA	.35	0.81	.07	.438	.664
	MBA	**7.25**	**3.11**	**.37**	**2.33**	**.025**
3	(Constant)	4.60	0.53		8.61	.000
	PHRA	0.57	0.82	.11	0.70	.491
	MBA	**6.59**	**3.13**	**.33**	**2.11**	**.043**
	IFGA	-3.08	2.48	-.20	-1.24	.222
4	(Constant)	8.75	1.24		7.08	.000
	PHRA	0.23	0.71	.05	0.33	.743
	MBA	**6.92**	**2.70**	**.35**	**2.57**	**.015**
	IFGA	-0.91	2.23	-.06	-0.41	.685
	Lunch Status	**-3.14**	**0.87**	**-.50**	**-3.62**	**.001**



F(1,38)=13.97, p=.001

Figure 3-3. Socioeconomic Effects on Kindergarten Spelling Performance

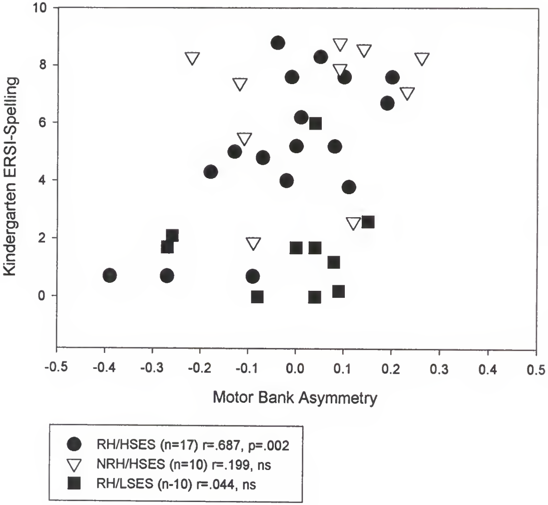


Figure 3-4. The Relationship of Kindergarten Spelling Performance to Motor Bank Asymmetry

(-.268, ns). This suggests that the MBA relationship to ERSI-Spelling is dependent on the left hemisphere motor bank.

Finally, motor bank asymmetry does not uniquely predict ERSI-spelling. There was not a significant relationship between motor bank asymmetry and ERSI-spelling when sensory bank asymmetry is partialed out of the relationship. This result is not surprising since the sensory bank is the opposing wall to the motor bank that creates the central sulcus.

Summary. Hypothesis one was not confirmed. Planar asymmetry did not predict pre-reading spelling performance. The motor bank asymmetry, among right-handed children not receiving lunch subsidy, predicted kindergarten spelling and was redundant with sensory bank asymmetry. SES predicted the most variance in ERSI-spelling performance.

Hypothesis 2

Leftward asymmetry of the PHRA was predicted to be positively related to Phase 2 (First Grade) reading performance. Data analysis from hypothesis 1 emphasized that hand preference plays a significant effect on the direction of the asymmetries with respect to behavioral performance. In addition, the sample size drops by 11 subjects because not every subject participated in Phase 2 of the study. The decreased sample size prevents the use of same regression model that was used in hypothesis 1. The relationship of the Phase 2 Word Attack, Word Identification, and Passage Comprehension scores to PHRA and the other anatomical asymmetries are presented as pearson correlations in Tables 3-6 and 3-7 for each hand preference group.

Table 3-6. Anatomical correlations with Phase 2 Woodcock-Johnson Reading Tests of Achievement for Right-Handed Subjects (N=21).

	PHRA	PARA	IFGA	MBA	SBA	OSA
Word Attack	r=.183 ns	r=-.395 p=.076	r=-.333 ns	**r=.461** **p=.036**	r=.412 p=.063	r=-.050 ns
Word ID	r=.093 ns	r=-.149 ns	r=-.162 ns	**r=.461** **p=.036**	r=.303 ns	r=-.420 p=.065
Passage Comp.	r=.039 ns	r=-.069 ns	r=-.229 ns	**r=.503** **p=.020**	**r=.465** **p=.033**	r=-.382 p=.096

Table 3-7. Anatomical correlations with Phase 2 Woodcock-Johnson Reading Tests of Achievement for Non-Right-Handed Subjects (N=12).

	PHRA	PARA	IFGA	MBA	SBA	OSA
Word Attack	r=.066 ns	r=.049 ns	r=-.534 ns	r=-.075 ns	r=.062 ns	r=-.408 ns
Word ID	r=-.030 ns	r=-.222 ns	r=-.542 ns	r=-.061 ns	r=-.030 ns	r=-.163 ns
Passage Comp.	r=.185 ns	r=-.073 ns	r=-.470 ns	r=.013 ns	r=-.042 ns	r=.029 ns

Table 3-6 and 3-7 demonstrate that there is no linear relationship between PHRA and the Woodcock-Johnson Reading Tests of Achievement in either hand preference group. However, there was a significant effect of MBA and SBA on the reading tests. When the effects of SBA are partialed out of the correlation between MBA and the reading tests there is no longer a significant effect of MBA on the reading tests (Word Attack r=.306, ns; Word ID r=.369, ns; Passage Comprehension r=.330, ns). This analysis suggests SBA and MBA are accounting for the same variance in phase 2 reading test performance. Partialing the effects of PHRA had no effect on the significance of MBA with reading test performance, but did result in a nonsignificant effect of SBA with Word ID (r=.291, ns).

Multiple regressions were run to determine the contribution of SES to phase 2 reading skill, in addition to MBA, for the right-hand preference group (This analysis was not possible for the non-right-handed children because of the low number of subjects). SES and MBA each significantly predicted a unique amount of variance in the Word Attack, Word ID, and Passage Comprehension subtests. The results of these regressions are presented in Appendix B.

Summary. Hypothesis two was not confirmed. Planar asymmetry did not predict phase 2 reading skill performance on the Woodcock-Johnson Tests of Reading Achievement. Motor and sensory bank asymmetry did significantly predict 1st grade reading skill performance. Lunch subsidy status once again predicted reading skill performance.

Hypothesis 3

Anatomical and behavioral correlations

Leftward asymmetry of the PHRA was predicted to be positively related to Phase 3 (6th grade) reading skills. The significant Pearson r relationships are presented by hand preference group and lunch subsidy grouping in Table 3-8. Graphical representations of representative significant PHRA effects are presented in Figures 3-5 through 3-11.

Table 3-8. Summary of Significant Neuroanatomical and Phase III Reading Skill Correlations by Hand Preference and Lunch Subsidy Grouping.

	PHRA	PARA	MBA	SBA	IFGA	OSA
Word Attack	RH (b)	NRH	RH (a)	-	-	-
Word ID	RH (a,b) NRH	RH (a) NRH	RH (a)	-	-	-
Passage Comp.	RH (a,b)	RH (a)	-	RH (a)	-	-
Phoneme Reversal	RH (a,b)	RH (a)	-	--	-	-
LACT	RH (a)	RH (a,b)	-	-	-	-
Digit Span (forward)	-	RH (a)	-	-	-	-
RAN letters	-	RH	NRH	-	-	-
RAN numbers	-	RH	NRH (a)	-	-	-
RAN colors	-	-	-	-	-	-

Significant effects at alpha<.05 Small font=trend at alpha <.10

RH- right-hand preference NRH- non-right-hand preference

(a)-No Lunch Subsidy

(b)-Lunch Subsidy

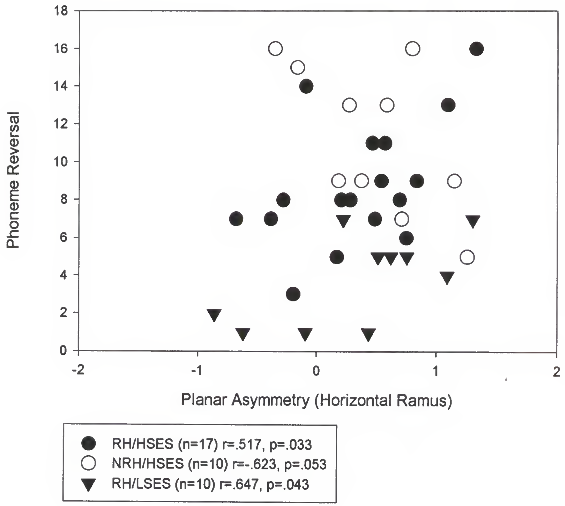


Figure 3-5. The Relationship of Phoneme Reversal to Planar Asymmetry by Hand Preference and Socioeconomic Status

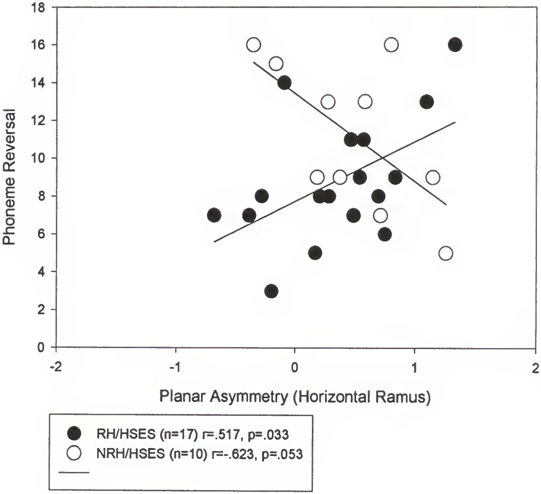


Figure 3-6. The Relationship of Phoneme Reversal to Planar Asymmetry in Right and Non-Right Handed Children Not Receiving Lunch Subsidy

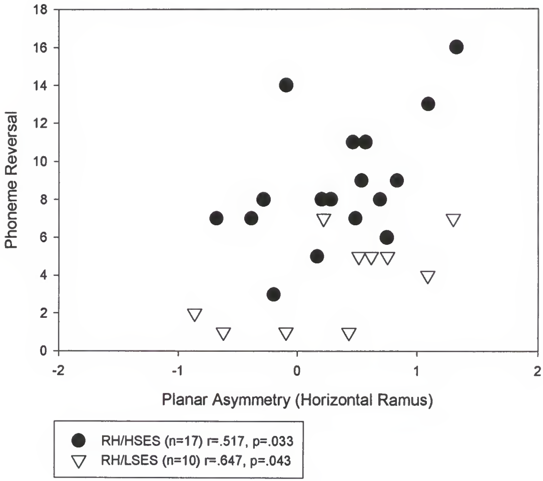


Figure 3-7. The Relationship of Phoneme Reversal to Planar Asymmetry in Right Handed Children by SES (Lunch Subsidy)

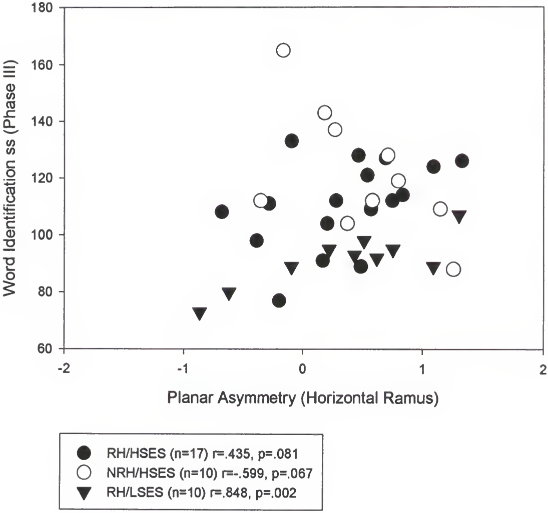


Figure 3-8. The Relationship of Phase III Word Identification to Planar Asymmetry by Hand Preference and Lunch Status

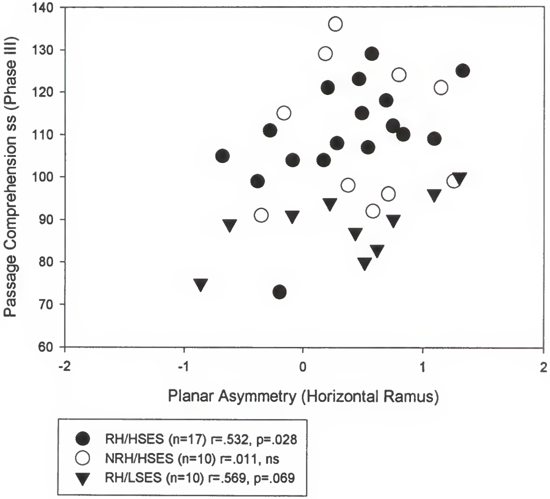


Figure 3-9. The Relationship of Phase III Passage Comprehension to Planar Asymmetry by Hand Preference and Lunch Status

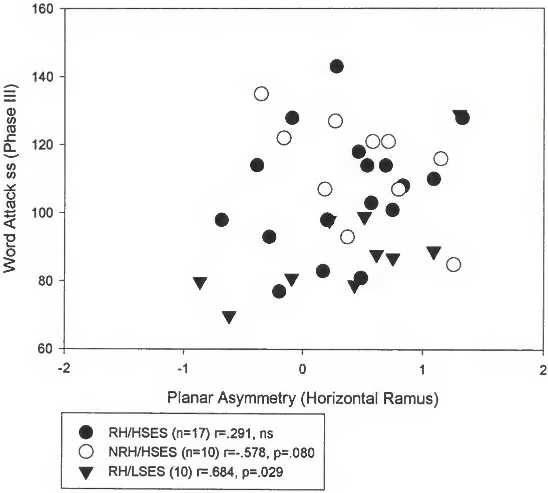


Figure 3-10. The Relationship of Phase III Word Attack Performance to Planar Asymmetry by Hand Preference and Socioeconomic Status (Lunch Subsidy)

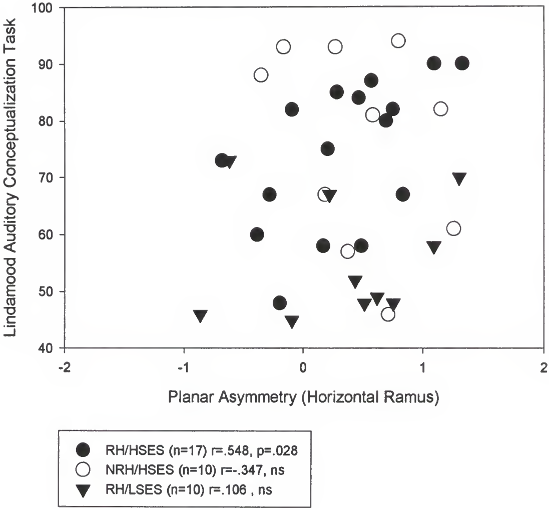


Figure 3-11. The Relationship of Phase III Lindamood Auditory Conceptualization Task to Planar Asymmetry by Hand Preference and Lunch Status

Table 3-8 demonstrates that PHRA and PARA are consistent predictors of phonological awareness across different tasks. However, PHRA was not a predictor of other phonological processing skills such as the RAN (phonological recoding in lexical access) and only NLS subjects demonstrated a significant relationship of PARA to digit span (phonological recoding in working memory).

There were few significant relationships (alpha=.05) for NRH. However, all the relationships involving PHRA and phonological awareness (those significant, trends, and non-significant) demonstrated a reversed slope from that of the RH children. NRH children with rightward asymmetry or symmetrical PHRA were better performers on the phonological awareness tasks than NRH with leftward asymmetry. The failure to demonstrate effects across all phonological tasks in NRH (n=12) is most likely due to a lack of power.

Reading skill/intelligence specificity

Correlations of the anatomical variables with FSIQ and the individual WISC subtests revealed that the Information subtest was related to PHRA in RH (r=.443, p=.021;No Subsidy r=.529, p=.029; full or partial lunch subsidy r=.677, p=.032). This relationship was not present in NRH subjects. Figure 3-12 demonstrates the relationship of PHRA to WISC Information for the RH subjects. Figure 3-12 is similar to the reading skill and PHRA graphs. There were main effects of PHRA and family income (lunch subsidy) on Information performance.

FSIQ and two of the subtests, Block Design and Similarities, were not related to PHR (see Figure 3-13). This suggests that PHRA does not account for a general

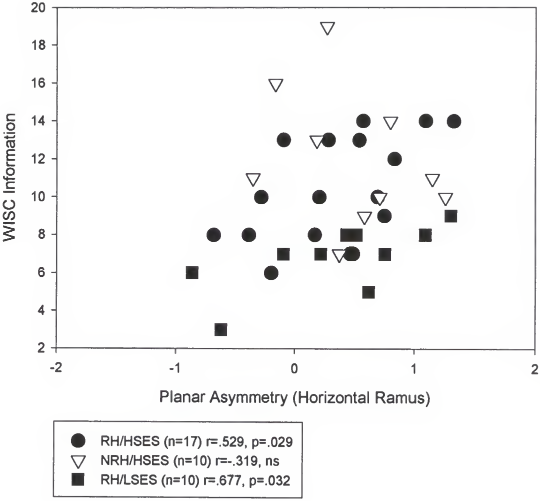


Figure 3-12. Relationship of WISC Information to Planar Asymmetry by Hand Preference and Lunch Status

intelligence factor. The most plausible explanation for the Information and PHRA relationship is an indirect relationship between reading skill and PHRA. Because reading skills (phonological awareness) are critical to reading comprehension, and reading provides children with information about the world (the correlation between Passage Comprehension and Information was r=.655, p<.001), reading skills and information should be accounting for the same variance in PHRA. To test this hypothesis, the effects of phonological awareness was partialed out of the relationship between Information and PHRA.

There was no longer a significant relationship between Information and PHRA when controlling for phonological awareness (controlling for Word Attack r=.247, ns; controlling for Phoneme r=.257, ns). These results demonstrate that PHRA predicts variance common to Information performance and tasks assessing phonological awareness.

The redundancy between phonological awareness and Information may have been related to a general verbal deficit, and not specifically between phonological awareness and Information. Partial correlations were run to pull out the effects of Block Design and Similarities WISC subtests on the PHRA and phonological awareness relationships. The significant relationships between PHRA and the phonological measures remained significant when variance shared by Block Design was controlled (Phoneme Reversal r=.544, p=.004; Word Attack r=.423, p=.031). When performance on the Similarities subtest was controlled there was no longer a significant relationship between phonological awareness and PHRA. These results demonstrate that PHRA was related to verbal

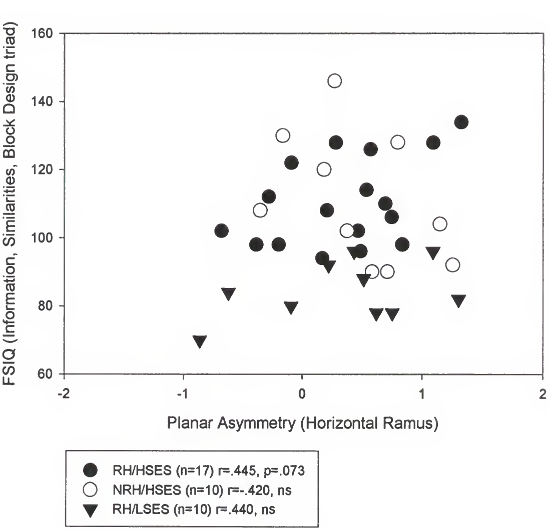


Figure 3-13. The Relationship of FSIQ to Planar Asymmetry by Hand Preference and Lunch Status

performance and not specifically related to phonological awareness. The results also suggest that PHRA is specifically related to verbal material and not to tasks assessing visuo-spatial performance.

Multiple regression: accounting for variance in reading skills.

A single phonological awareness variable was created to reduce the number of reported multiple regressions. This variable was the primary factor from a factor analysis of the 6th grade tests that assess phonological awareness (Eigenvalue=3.17, 79% variance accounted for; Communalities = Word Attack (.779), Word Identification (.763) Phoneme Reversal (.864), and the LACT (.767). Figure 3-14 presents the relationship of the phonological factor to PHRA by hand preference and lunch status for comparison to the individual phonological tasks. Regressions for each of the phonological tasks are presented in the Appendix.

The multiple regression predicting the phonological factor was significant (R=.754, F=11.19, p<.001). Planar asymmetry, hand preference, an interaction between planar asymmetry and hand preference, and lunch status all uniquely and significantly predicted the phonological factor (see Table 3-10). Figure 3-15 displays the relationship between the regression model and the phonological factor.

Table 3-9. Coefficients For Regression Analysis of the Phonological Factor.

Variables	B	Std Error	Std. B	t	Sig.
(Constant)	-0.39	0.55		-0.71	0.480
Hand Preference	**1.32**	**0.30**	**0.62**	**4.38**	**0.001**
PHRA	**2.33**	**0.60**	**1.33**	**3.89**	**0.001**
PHRA * Hand Pref.	**-1.64**	**0.44**	**-1.33**	**-3.71**	**0.001**
Lunch Status	**-1.05**	**0.25**	**-0.49**	**-4.23**	**0.001**

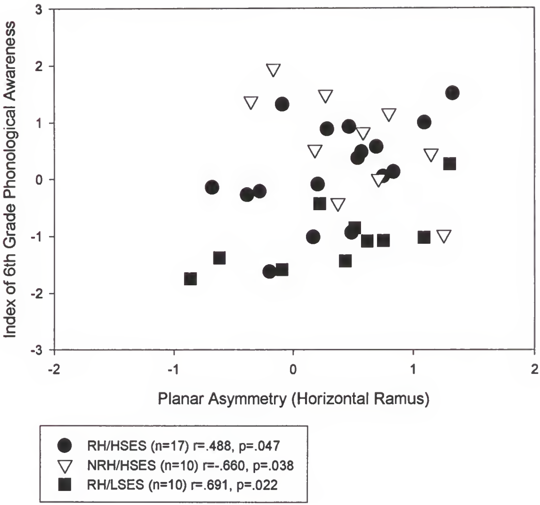
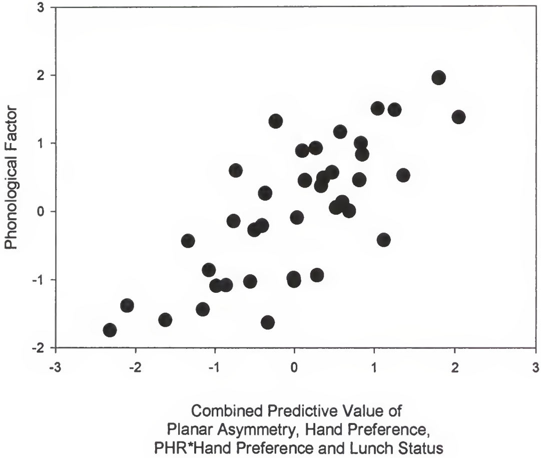


Figure 3-14. The Relationship of the Index of Phonological Awareness to Planar Asymmetry by Hand Preference and Lunch Status



R=.754; F=11.19, p<.001

Figure 3-15. Neuroanatomical, SES, and Hand Preference Prediction of Phonological Awareness

Lunch status was used as the SES variable in the model because of the results from a previous regression. The Hollingshead index of SES and lunch status were entered in this regression at the same time. The result was significant (R=.562; F=8.30, p=.001) and the betas demonstrated that Hollingshead SES was redundant with lunch status (Std B=.258; t=1.47, p>.05) and lunch status predicted unique variance in the phonological factor (Std B=-.364; t=-2.07, p=.045).

There were no other control variables entered in the analysis because of sample size constraints. Separate regressions were run with only the anatomical and interaction terms in order to determine the specificity of relationship of PHRA to the phonological factor. The control variables were entered in the second level of the regression in order to determine if they significantly added to the model by predicting a unique amount of variance. Table 3-10 provides a summary of those results by highlighting the anatomical variables that predicted the same variance as PHRA (resulting in a non-significant PHRA beta) or were not related to the phonological factor. PARA predicted the same variance in the phonological factor as PHRA predicted. MBA and SBA approached predicting a unique amount of variance and simultaneously diminished the strength of the significant PHRA beta. However, neither SBA or MBA predicts a significant amount of variance when PHR is not in the regression.

Table 3-10. Neuroanatomical Variables Demonstrating Redundancy with PHR.

	PARA	MBA	SBA	IFGA	OSA
Non-significant Rsq Change & *Significant* PHRA Beta		X beta=.842 p=.053	X beta=.746 p=.078	X	X
Non-significant Rsq Change & *Non-significant* PHRA Beta (Redundancy)	X				

The same regression model was used to predict FSIQ in order to determine if PHR is specific to phonological processing or related to general intellectual ability. The model was significant when SES was entered with PHRA, hand preference group and the interaction between PHRA and hand preference interaction (R=653, p=.001). However, neither PHRA or the interaction variable significantly predicted FSIQ at any level of the regression.

Is size of structures important to the prediction of phonological awareness?

The previous analyses demonstrated significant relationships between the phonological factor and hemispheric asymmetry of the sylvian fissure (PHRA & PARA) among children with a right-hand preference. Simple Pearson r correlations were run to determine if the asymmetry correlations are driven by the left, right or both regional surface areas. The correlations were followed by stepwise regressions to determine which variable accounted for the most variance in the phonological factor.

The right PHR surface area (-.389, p<.05), not the left (r=.146, ns), was related to the phonological factor. A larger right PHR was associated with poor phonological awareness in right-handed children. However, the stepwise regression revealed that PHRA accounted for more variance than the right PHR surface area. This result suggests that while the right PHR is the strongest contributor, the PHRA relationship is still dependent on the left PHR.

Neither the left (r=-.298, ns) or the right PAR (r=.208) was significantly related to the phonological factor. The relationship of PARA to the phonological factor is dependent on the contribution of both the left and right PAR.

Summary. Hypothesis 3 was confirmed. PHRA was related to 6th grade reading skills. The data demonstrate main effects of SES and PHRA, with an interaction between PHRA and hand preference. RH children with symmetry or rightward PHRA had the worst phonological skill if they were low SES. A higher SES increased performance to normal levels among symmetrical or rightward RH children. RH children with leftward asymmetry and a high SES exhibited the best phonological skills. Children with leftward asymmetry and a low SES performed at normal levels.

The results of the control analyses were mixed. The unstable multiple regressions suggest that MBA and SBA predicted a unique amount of variance in phonological skills. The IFGA and OSA were not related to reading skill. Finally there was no relationship of FSIQ to PHRA (most likely due to the contribution of Block Design performance). A lack of a relationship between FSIQ and PHRA does not rule out the likelihood that PHRA is also related to verbal intelligence. The within group correlations demonstrated a significant relationship between PHRA and the Information subtest among RH children.

Hypothesis 4

6th grade reading skills were predicted to demonstrate a stronger relationship with PHRA than kindergarten or 1st grade reading skill. Multiple regression analysis was used to examine this hypothesis. The previous analyses demonstrated an interaction between PHRA and hand preference. The hand preference and the interaction variables were entered in level 1 of a hierarchical regression to unmask the relationship of PHRA with the phonological variables. The phonological variables were entered in level 2 of the regression. The variables entered in level 2 included kindergarten ERSI-spelling performance, a 1st grade factor analysis variable from the common construct of the WJ-Word Attack and Word Identification, and the 6th grade phonological factor used in hypothesis 3. Hand preference and the interaction with PHRA accounted for the majority of the variance. Therefore, the multiple R was not of value. Additional variance predicted by the phonological variable was used to address hypothesis 4.

Level 2 of the regression demonstrated that only the 6th grade phonological factor predicted a unique amount of variance in PHRA (Std. B=.255; t=2.65, p=.015). The betas for kindergarten spelling performance and the 1st grade phonological factor were not significant. The betas for the kindergarten and 1st grade variables remained non-significant when the 6th grade phonological factor was removed from the model.

These results confirm the hypothesis that 6th grade reading skills would be most strongly related to the PHRA measurement obtained from a 6th grade MRI. This result was evident from the analyses of hypotheses 1 through 3. The simple Pearson correlations run for those analyses demonstrated significant PHRA relationship with only 6th grade reading skills.

In kindergarten, SES was the dominant predictor of Spelling performance. The 1st grade data are difficult to interpret because of the drop in sample size and power.

Hypothesis 5

Children whose reading skills were consistently below average across development were predicted to have significantly less leftward asymmetry than children performing at normal or superior reading skill levels. To test this hypothesis, the sample was spit into children whose reading skills were 1 standard deviation below average in kindergarten and 6th grade were included in a low performance group (N=9) (This group included a child who had average reading skills in kindergarten and fell below 1 standard deviation in 6th grade). A high performance group (N=30) included children who performed within the average range or 1 standard deviation above the norm across development (This group included children who increased from average to above average performance and children who decreased to average performance from above average in kindergarten. This grouping was based on the assumption that children declining from above average to average across development are just regressing to the mean). The low performance group was predicted to have a significantly less leftward planar asymmetry than the high performance groups. ANOVA was used to compare the two groups on the coefficient of planar asymmetry.

There was no group difference for any neuroanatomical asymmetry in the entire sample. Previous analyses demonstrated the influence of hand preference on the relation between asymmetry direction and to reading skill performance. Therefore, the same ANOVA design was used for each hand preference group. Table 3-11 presents the ANOVA results for each of the neuroanatomical asymmetry variables for RH children. PHR was the only neuroanatomical variable that exhibited significantly more leftward asymmetry in the high performance group than the low performance group. Figure 3-16 provides a graphical representation of this difference. The same analyses could not be performed for the non-right-handed children because only 1 non-right-handed child was in the low performance group.

Table 3-11. ANOVA Results Comparing the Planar Asymmetry of Right-Handed Children With Low vs. High Reading Skills Across Development.

	df	F	Sig.
PHRA	(1,26)	**4.450**	**0.045**
MBA	(1,26)	2.850	0.104
SBA	(1,26)	1.596	0.218
OSA	(1,25)	0.076	0.785
PARA	(1,26)	1.331	0.260
IFGA	(1,26)	0.030	0.863

Hypothesis 5-a:

Hypothesis 5 was proposed in order to examine how planar asymmetry related not just to performance but to the change in performance over time or rate of development. There were too few subjects who exhibited change in reading skill performance above or below 1 standard deviation across development to compare with regard to their neuroanatomy. To circumvent this problem and examine change in performance between

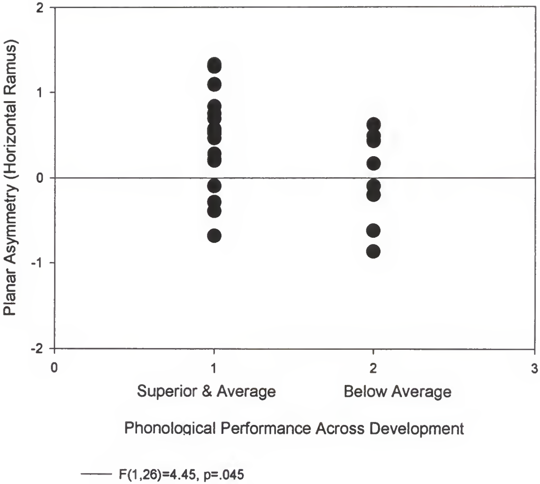


Figure 3-16. Difference in Planar Asymmetry Between Right Handed Phonological Development Groups

kindergarten and 1st grade, the kindergarten ERSI-Spelling subtest z-score was subtracted from the phonological factor (discussed in Hypothesis 3). This transformation was performed based on the assumption that spelling measures the same basic skill that makes up the phonological factor. ERSI-Spelling was significantly related to the 6th grade phonological factor ($r=.756$, $p<.001$) and was entered in the primary factor when included in the factor analysis of the 6th grade phonological variables.

Phonological change was predicted using the same regression model that was used in hypothesis 3. PHRA and hand preference were entered in level one of the regression. The PHRA and hand preference interaction was entered in level 2, and lunch status was entered in level 3.

The results were identical to regression results for the phonological factor in hypothesis 3, with the exception that lunch status was not a significant predictor of phonological change. Table 3-12 demonstrates that PHRA, hand preference, and the PHRA and hand preference interaction all predict a significant and unique amount of variance in phonological change. Although lunch status was not a significant predictor (no main effect to increase or decrease the phonological change index), the PHRA relationship with phonological change was strongest among children receiving lunch subsidy (no subsidy, $r=.223$, ns; subsidy, $r=.758$, $p=.011$). Figure 3-17 displays a graphical representation of this result. The regression line for both lunch status groups is identical, but the data for the children receiving lunch subsidy exhibits a tighter fit along the regression line.

Table 3-12. Regression Results Predicting Phonological Change.

R=.628; F=5.25, p=.002					
	B	Std. Error	Beta	t	Sig.
(Constant)	-1.879	0.580		-3.242	0.003
PHRA	**1.932**	**0.632**	**1.241**	**3.058**	**0.004**
Hand Preference	**1.464**	**0.318**	**0.767**	**4.600**	**0.000**
PHRA*Hand Preference	**-1.451**	**0.469**	**-1.313**	**-3.058**	**0.004**
Lunch Status	-0.001	0.262	-0.009	-0.063	0.950

To determine the specificity of the PHRA relationship to the index of phonological change, lunch status was removed from the regression model and replaced with MBA, SBA, IFGA, OSA or PARA and their respective handedness interaction terms. The R square change and betas for each analysis are presented in Table 3-13. MBA added a significant amount of unique variance to the prediction of the index of phonological change. IFG and OSA did not add a significant amount of variance, nor were they redundant with PHRA. However, PARA was redundant with PHRA and predicted more variance than PHRA. The reason for this result is that PARA significantly predicted the index of phonological change in both right and non-right-handed subjects (figure 3-18) while PHRA significantly predicted phonological change only in right-handed subjects (figure 3-19).

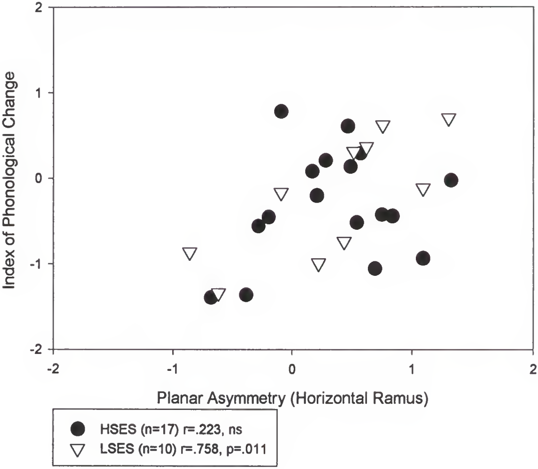
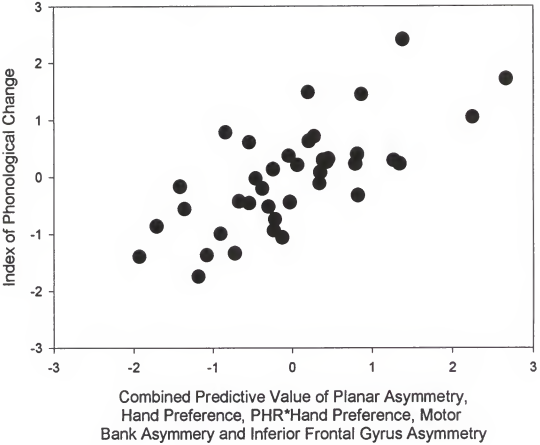


Figure 3-17. Relationship of Phonological Change Between Kindergarten and 6th Grade to Planar Asymmetry Among Children with a Right Hand Preference



R=.706; F(1,38)=6.55, p<.001

Figure 3-18. Neuroanatomical and Hand Preference Prediction of Change In Phonological Awareness Between Kindergarten and Sixth Grade

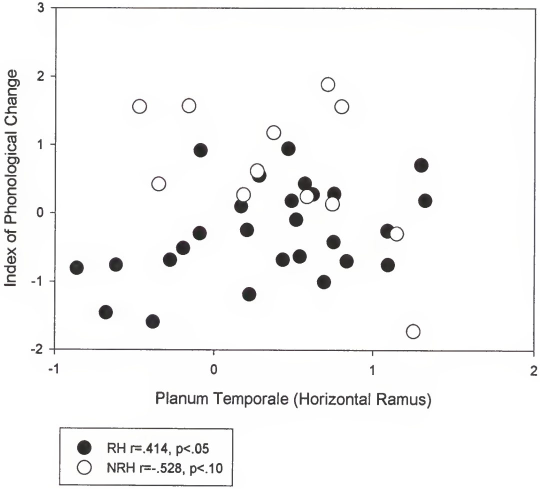


Figure 3-19. The Horizontal Ramus of the Planum Temporale Predicts the Index of Phonological Change Right and Non-Right-Handed Subjects

Table 3-13. Regression Results for Control Neuroanatomical Variables and the Respective Hand Preference Interaction Terms Predicting the Index of Phonological Change.

	MBA	IFGA	SBA	PARA	OSA
R	**.721**	**.688**	.684	.709	.664
R square change	**.126**	**.079**	.074	.109	.048
F change	**4.33, p=.021**	**2.48, p=.099**	2.23, ns	3.52,p=.041	-1.34, ns
Std. Beta	**-.274,p=ns**	**.030, p=.047**	-.151, ns	-1.38,p=.013	-.716, ns

Only neuroanatomical variables are presented.
Significant F change occurs without significant beta because the neuroanatomical beta is redundant with the hand preference interaction term.

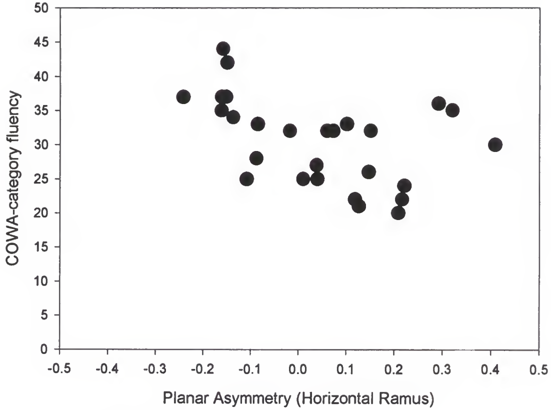
Summary. Hypothesis 5 was confirmed. Children (RH) who demonstrated below average reading skill from kindergarten to 6th grade had plana with significantly less leftward asymmetry. Further, there was a significant linear relationship between children's rate of phonological development and their planar asymmetry. Coupled with the hypothesis 3 results, the data suggest that children with reversed asymmetry exhibit reading skills that are below the average of their peers with normal planar asymmetry and that their reading skills have not developed at the same rate as children with normal asymmetry.

There was no difference in the index of phonological change across lunch status groups. This result suggests that although SES is related to reading performance at a given time point, planar asymmetry is a stronger influence on the amount of reading skill development that occurs from kindergarten to 6th grade. However, there was a stronger linear relationship between the index of phonological change and PHRA among children receiving lunch subsidy.

Hypothesis 6

Hypothesis 6 proposed that there would be a significant relationship of speech production and naming skill to pars triangularis asymmetry. This exploratory hypothesis was not and could not be directly examined with the following analyses. Measurement reliability could not be obtained for pars triangularis. However, reliability was obtained for the surface area of the inferior frontal gyrus. This measurement includes the surface area of pars triangularis and pars opercularis. Simple correlations of the speech production and naming skills with the neuroanatomical variables by hand preference group were examined first. Regression analysis was then used to explore the significant correlations. Tables 3-14 and 3-15 present the correlations between the production and neuroanatomical variables for right-handed and non-right-handed children. The IFGA was related to producing words that were animals, vegetables and fruits or category words among right-handed children only. Rightward asymmetry was related to better speech production performance. This effect remains significant when the effects of PARA are removed in a partial correlation (r=-.521, p=.008). However, the relationship is most likely driven by the right hemisphere. The right IFGA (r=.462, p=.015), and not the left IFG (r=.127, p>.05), demonstrated a significant relationship with COWA category. Figure 3-20 displays the relationship between IFGA and category fluency.

Surprisingly, the majority of the speech production and naming tasks were significantly related to PARA. Rightward PARA was associated with better fluency and naming performance. This effect remained significant when the effect of IFGA was



r=-.467, p=.014

Figure 3-20. Relationship of Category Fluency to Inferior Frontal Gyrus Asymmetry Among Right Handed Subjects

controlled (RAN letters, r=.478, p=.014; RAN numbers, r=.428, p=.029; COWA Category, r=-.446, p=.022). Figures 3-21 through 3-23 demonstrate these significant PAR relationships. The PARA effect is dependent on both the left and right PAR. Neither the left or the right PAR was significantly related to the behavioral variables. The other neuroanatomical variables were not related to any production tasks performed by right-handed children.

Table 3-14. Neuroanatomical Correlations with Speech Production and Naming Tasks Among Right-Handed Children.

	IFGA	PHRA	PARA	MBA	SBA	OSA
RAN Colors	-.059 ns	-.096 ns	.359, p=.066	-.053 ns	.169 ns	.144 ns
RAN Letters	.256 ns	-.208 ns	**.458,** **p=.016**	-.137 ns	-.032 ns	.210 ns
RAN Numbers	.169 ns	-.199 ns	**.420,** **p=.029**	-.001 ns	.026 ns	.123 ns
COWA Category	**-.467,** **p=.014**	.106 ns	**-.389,** **p=.045**	.294 ns	.256 ns	-.232 ns
COWA FAS	-.089 ns	.342, p=.081	-.259 ns	.280 ns	-.025 ns	.038 ns

The simple correlations for the non-right-handed children are difficult to interpret because of the small sample size. Only MBA and RAN letters exhibit a significant correlation. Children with a stronger leftward asymmetry of the MBA took longer to complete naming letters. However, this effect disappeared when controlling for IFGA (r=.5044, p>.05).

Table 3-16 presents the results of the regression analysis used to predict word category fluency. Hand preference, IFGA and PARA were entered in the first level of the analysis. These variables did not predict fluency. However, the model does become significant when the hand preference and neuroanatomical interaction variables are entered.

Hand preference and the interaction terms unmask the relationship of IFGA and PARA to category fluency. This analysis emphasizes the previous correlation results that the neuroanatomical relationships with category fluency are only seen within hand preference groups.

Table 3-15. Neuroanatomical Correlations with Speech Production and Naming Tasks Among Non-Right-Handed Children.

	IFGA	PHRA	PARA	MBA	SBA	OSA
RAN Colors	.090 ns	.207 ns	-.105 ns	.094 ns	.060 ns	.045 ns
RAN Letters	-.471 ns	.045 ns	-.151 ns	**.622,** **p=.031**	.408 ns	.173 ns
RAN Numbers	-.502, p=.097	.267 ns	-.364 ns	.543, p=.068	.326 ns	.300 ns
COWA Category	.060 ns	-.336 ns	.342 ns	.215 ns	-.079 ns	-.067 ns
COWA FAS	.374 ns	-.269 ns	.468 ns	-.060 ns	.006 ns	-.239 ns

Table 3-16. Regression Analysis Results Predicting Category Fluency.

R=.612, Rsq=.374; F=3.19, p=.014

Model Level	Variables	B	Std. Error	Std. B	t	Signif.
1	(Constant)	27.962	3.218		8.690	0.000
	HP	2.661	2.296	0.184	1.159	0.254
	IFGA	-8.733	5.729	-0.242	-1.524	0.136
	PARA	-1.129	1.241	-0.144	-0.909	0.369
2	(Constant)	32.537	4.505		7.223	0.000
	HP	3.450	2.232	0.238	1.545	0.132
	IFGA	-30.396	15.659	-0.843	-1.941	0.061
	PARA	**-9.062**	**3.434**	**-1.159**	**-2.639**	**0.013**
	Lunch Status	-3.997	2.191	-0.276	-1.825	0.077
	IFGA*HP	15.249	10.525	0.635	1.449	0.157
	PARA*HP	**6.614**	**2.671**	**1.119**	**2.476**	**0.019**

HP-Hand Preference

Instead of running 3 regressions for each RAN test (colors, letters, numbers), a factor analysis was performed on the three variables to extract the common variance among the 3 naming tasks. A single factor was extracted from the analysis (component matrix values: RAN colors=.772, letters=.915, numbers=.899). The primary factor was used as the naming speed dependent variable in the following regression. The same model that was used for the fluency regression was used for this naming speed regression. Table 3-17 presents the results of the naming speed regression. Although the PARA Beta is significant, the model did not significantly predict naming speed. The model was not significant because the number of variables that did not contribute reduced the power of the model, washing out the PARA effect.

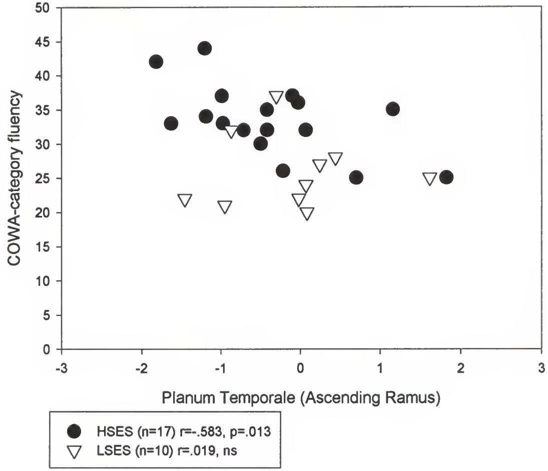
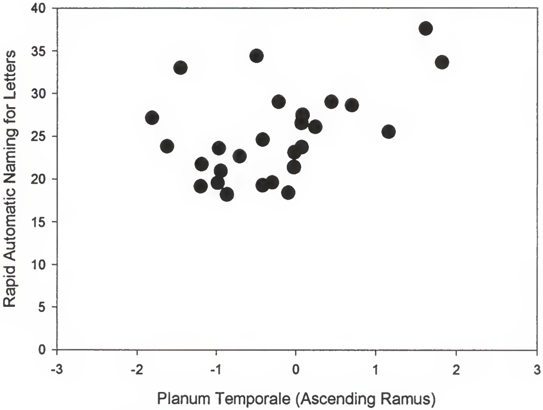
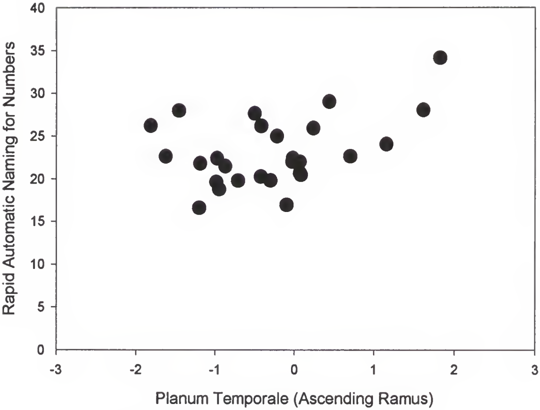


Figure 3-21. The Relationship of Category Fluency to Planum Temporale (Ascending Ramus) Asymmetry



r=.458, p=.016

Figure 3-22. The Relationship of Letter Naming Speed to Planum Temporale (Ascending Ramus) Asymmetry



r=.428, p=.029

Figure 3-23. The Relationship of Number Naming Speed to Planum Temporale (Asceding Ramus) Asymmetry

Table 3-17. Regression Analysis Results Predicting Category Naming Speed.

R=.467, Rsq.218; F=1.49, p>.05

Model Level	Variable	B	Std. Error	Std. B	t	Signif.
1	(Constant)	0.238	0.490		0.486	0.630
	HP	-0.108	0.350	-0.051	-0.310	0.758
	IFGA	-0.373	0.872	-0.070	-0.428	0.671
	PARA	0.293	0.189	0.254	1.552	0.130
2	(Constant)	0.181	0.743		0.244	0.809
	HP	-0.239	0.368	-0.112	-0.649	0.521
	IFGA	3.217	2.583	0.605	1.245	0.222
	PARA	**1.234**	**0.567**	**1.069**	**2.177**	**0.037**
	Lunch Status	0.141	0.361	0.066	0.391	0.698
	PARA*HP	-0.750	0.441	-0.859	-1.701	0.099
	IFGA*HP	-2.409	1.736	-0.680	-1.387	0.175

PARA significantly predicted fluency and naming speed. To determine if PARA is predicting variance common to fluency and naming speed, fluency and naming speed were entered as independent variables in a regression designed to predict PARA among right-handed children (only RH children because of the hand preference interaction). The model was significant (R=.511, Rsq=.261; F=4.25, p=.026). However, the betas demonstrated that fluency and naming speed were predicting the same variance in PARA (fluency B=-.203, p>.05; naming speed B=.380, p>.05).

Summary. Hypothesis 6 was partially confirmed. IFGA and PARA were related to category fluency among right-handed children. Rightward asymmetry was associated with better fluency. PARA and IFGA each uniquely added to the prediction of category fluency.

However, fluency related to words beginning with the letters F, A, and S was not related to any neuroanatomical variable. The prediction that IFGA would be related to naming speed was also not confirmed. However, speed of naming was related to PARA among right-handed children.

The IFGA data suggests that fluency, not naming speed skills, was specifically related to the region of the IFGA that was measured. Both fluency and naming speed were related to PARA, but were redundant. PARA predicted variability common to fluency and naming speed.

Figure 3-24 presents a summary of significant paths among the behavioral and anatomical variables.

Table 3-18. Summary of Results for Each Hypothesis.

Hypothesis	Confirmation?	Finding 1	Finding 2
1	Not Confirmed	MBA asymmetry related to K spelling (in HSES-RH)	Lunch Status best predictor
2	Not Confirmed	MBA asymmetry related to 1st Grade WJ-Reading Achievement (in RH)	Lunch Status also a significant predictor
3	Confirmed	PHRA related to 6th grade reading skills, but not specific (PARA related)	Lunch status also a significant predictor
4	Confirmed	6th grade reading skills demonstrate the strongest relationship with PHRA	
5	Confirmed	Difference in PHRA between low and high developmental reading skill groups	PHRA significantly related to an index of phonological change between kindergarten and 6th grade. No main effect of lunch status, but stronger relationship for children receiving lunch subsidy
6	Partially Confirmed	IFGA related to category fluency, not letter fluency or naming speed	PARA related to common variance in fluency and naming speed

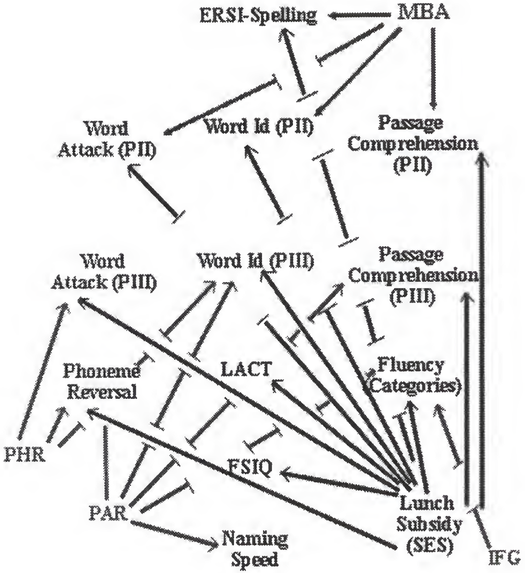


Figure 3-24. Significant Paths Among Behavioral and Anatomical Variables

CHAPTER 4
DISCUSSION

Why do some children read at every opportunity while others fail to become literate? There are many reasons for reading difficulty, and an impoverished environment is a frequent explanation. But there has not been a clear understanding as to why one child might have a "natural ability" for reading when another child from the same background has difficulty learning to read. The results of this project demonstrate that reading skills are associated with a child's environment and neuroanatomy. Children with environmental and biological risk factors were in danger for reading failure. However, the results also show that the presence of a biological risk factor does not prevent children from learning to read.

The relationship of brain structure to reading skill also suggests an optimal organization of the brain for processing linguistic information. The directions of hand preference and cerebral asymmetry were critical to predicting reading skill. Children had elevated phonological skills only when hand and brain asymmetries were congruent.

The congruent asymmetry effect also impacted the association between planar asymmetry and improvement in phonological processing between kindergarten to 6th grade. The results showed that brain asymmetry could predict the reading skill rate of development and performance between kindergarten and 6th grade. Across the socioeconomic strata, asymmetry of the planum temporale was significantly related to reading skill development.

The subjects participating in this study represent a unique representative sample of children in the Alachua County Fl. public school system. The sample is unique because the participants were tested for their reading skills in kindergarten, 1st grade and 6th grade. During the 6th grade phase of the study the children received an MRI that provided the opportunity to examine individual differences in neuroanatomy and reading skill. The following sections discuss these and other findings.

Behavioral Associations

There were strong relationships among nearly all of the behavioral measures. These results were not surprising given that many of the variables measured similar constructs. This section will review the longitudinal results and the application of the behavioral results to the findings and issues in the reading development literature.

Kindergarten Spelling Predicts Future Phonological Skill

Kindergarten spelling performance predicted nearly every 1st and 6th grade verbal behavioral variable. The critical variable that explained the strong relationships among all of the variables was FSIQ. The argument could be made that reading skills are necessary to provide a child with the ability to read to learn about the world, thereby increasing vocabulary and knowledge about the world. However, dyslexics have phonological impairment in the absence of low IQ. Some dyslexics are successful at reading because they can overcome their phonological impairment by using context to find meaning in text (Ferri, 1997). Therefore the ability of some children to compensate for phonological skill deficits shows that there is not a concomitant decrease in IQ as a result of phonological skill impairment.

When FSIQ was controlled, there was no change in the highly significant relationship between kindergarten spelling and 1st grade passage comprehension (r=.922). In contrast, controlling FSIQ showed that kindergarten spelling and 6th grade phonological decoding failed to predict 6th grade reading comprehension. The association of phonological decoding and spelling to reading comprehension changes between the beginning and end of the elementary school years. This interpretation is supported by the literature reporting on the relationship of reading skills to future reading performance. MacDonald and Cornwall (1995) did not see a relationship between kindergarten spelling performance and reading achievement 11 years later. However, Shankweiler, (1995) did report that kindergarten phonological decoding significantly predicted 1st grade reading comprehension. In addition, Naslund and Schneider, (1996) reported that kindergarten and 1st grade phonological awareness was predictive of 2nd grade reading comprehension.

The relationship between phonological awareness and reading comprehension appears to become mediated by FSIQ later in life. The educational system, and probably environment in general, provides children the skills for acquiring literacty, but the degree of reading achievement is dependent on IQ. Interestingly, kindergarten spelling was also significantly related to 6th grade FSIQ. Excluding dyslexic children, early advantages in pre-reading spelling ability might be indicative of IQ and therefore reading success later in life.

Predictors of Behavioral Performance

SES was a strong predictor of behavioral performance from kindergarten to 6th grade. SES is frequently reported as a strong predictor of many psychological outcome measures (Ratusnik and Koenigsknecht, 1975; Alexander and Entwisle, 1988; Sahai, 1989; de Jong, 1993). This section discusses the role of SES and other demographic variables on test battery performance.

Children in this study qualified for lunch subsidy if they were from families classified as having a federally defined low income. Children receiving lunch subsidy performed significantly worse on all of the cognitive tasks. Previous studies examining the impact of SES on child development have noted maternal and paternal education as two of the strongest factors related to SES that predict their biological children's academic success (Fowler and Cross, 1986).

There are a number of reasons maternal and paternal education could have a negative impact on a child's achievement. Parents with less education tend to have lower paying jobs, represent the majority of single parent families, are more likely to work more than one job and have less time to devote to their children. These reasons could explain the finding from this study that low SES children had parents who spent significantly less time helping them with homework. Parents who invest little time in their children's academic activities have children who are not successful in school (Finn & Owings, 1991).

Parents with less education also have fewer books in the home (Blatchford and Farquhar, 1988). Low SES families in this study had fewer books in the home than high SES families. The number of books in the home has been reported as a strong environmental predictor of children's successful reading development (Weinberger, 1996). Exposure to books (Scarborough, 1991) and parental modeling (Thal & Bates, 1988) are critical for children to develop linguistic skills. Children who are early readers have parents who read for pleasure (Manning & Manning, 1984). Anecdotally, the family in this study with the fewest books and one of the lowest incomes, had the most televisions.

Findings from this study suggest parental investment is a critical factor in cognitive development. However, it is not simply the amount of time parents spend with their children. Distinctive ways of interacting with children are also critical to development (Snow, 1983; Peralta de Mendoza, 1995). Children who develop good verbal skills have mothers that use more demanding and elaborate language compared to low SES mothers (Peralta de Mendoza, 1995).

Differences in parental child interactions may suggest that communication styles are related to intellectual ability. The communication style and IQ relationship introduces the directionality problem with IQ and SES. Is IQ the result of SES influences on development? Or do people with low IQ aggregate in the low socioeconomic strata? The answer is probably yes to both questions. SES has been reported to impact academic achievement independently of IQ (Walker et al., 1994). And adoption studies demonstrate that adopted children exhibit significant relationships between their IQ and their biological, not adopted, parents' level of education (Scarr and Weinberg, 1983). Parents who have fewer books in the home and reached lower education levels are probably more likely to have low IQ and/or specific learning disabilities. Measuring parental IQ and SES would be one way to determine whether SES or IQ is mediating the effect on children's academic achievement.

Heritability

Parents who have low IQ and/or learning disability are more likely to have children with low IQ and/or learning disability (Light et al., 1998). Phonological impairment, a form of learning disability, is common among parents of probands with the oral-language deficit and among twins if one has oral-language impairment (Pennington and Smith, 1997). Data collected in this study support the heritability of phonological impairment. Eighty-nine percent (8/9) of children with clinically significant phonological impairment had parents report that other family members had reading or language problems. However, only 10% (3/30) of children performing within the normal range of phonological skill had parents report familial language impairment. The normal distribution of phonological performance and the high percentage of children with phonological impairment who have parents with phonological impairment suggests that a phonological phenotype might result from additive genetic effects.

Development of the phonological phenotype is also dependent on the childhood environment. 67% (6/9) of the phonologically impaired children were from low SES families. There were three unaffected children with a family history of language impairment. All three were from high SES families. These data parallel the anatomical data demonstrating that abnormal asymmetry of the planum temporale is predictive of phonological impairment when children are from low SES families. The same structural phenotype among high SES families was not related to phonological impairment, but was related to decreased ability relative to children with normal asymmetry. Therefore, although there may be additive genetic effects for phonological ability, the negative impact of receiving the "wrong" allele(s) is most evident among low SES children.

Hand Preference

This study yielded a surprising result with regard to SES. The majority of the NRH subjects were from high SES families. However, the distribution of hand preference to SES groups was not significant. The most probable explanation for the unbalanced sample was sample size. Nonetheless, the distribution of hand preference to different socioeconomic strata deserves a discussion of the mechanisms for hand preference development.

There is currently debate over the role of environment in establishing hand. The animal literature supports the influence of the environment on determining hand preference. Research using rats, mice, and cats has shown that hand (or paw) preference can be trained when food can only be obtained with one paw (Provins, 1997; Ward, 1985). These results are similar to a finding that experience (driving) alters footedness in left-handed adults (Gabbard and Hart, 1995).

The paw preference training data was collected in quadrupedal mammals. An evolutionary shift to bipedalism has been proposed as the critical factor influencing the development of hand preference (Corballis, 1995). Posture has been shown to impact the expression of hand preference in primates. Great apes, tufted capuchins, and rhesus monkeys exhibit a shift toward a right-hand bias during bipedal reaching tasks, but not quadrupedal reaching tasks (Westergaard et al., 1998).

The Westergaard, Kuhn & Suomi (1998) finding suggests that environmental pressures led to the expression of hand preference and potentially to genetic representation for hand preference. Hand preference is shared more frequently among monozygotic twins compared to dizygotic twins (Orlebeke et al., 1996), more likely to be transmitted by mothers to male offspring (McManus, 1995; Orlebeke et al., 1996) and is associated with alleles in the HLA region of chromosome 6 (Gangestad et al., 1996). However, the genetic and environmental mechanisms that interact to influence hand preference are not known.

Environmental factors believed to influence the expression of hand preference include prenatal insults and birth difficulties. Prenatal insults are also reported to alter hand preference in 1 out of 20 left handed people (McManus, 1981). Birth difficulties were not related to hand preference in this study. Three of the 12 NRH had parents report birth difficulties compared to 8/27 RH children experienced birth difficulties[1]. In addition, the degree of left handedness was not related to birth difficulty. Unfortunately, it was not possible to determine the role of the various contributing variables to the development of hand preference.

This section discussed the role of inter-related SES factors and hand preference on behavioral performance. SES has a strong effect on development that is the likely result of an interaction between environmental influences and biological factors that influence economic positions in society. A well-defined explanation of how these influences work to produce phonological impairment has not been presented in the literature. The following sections will describe the way the environment and biology influence phonological and reading development.

Neuroanatomic Predictors of Reading Skill Development

This section discusses the results of the kindergarten (Phase I), 1st grade (Phase 2) and 6th grade (Phase 3) relationships between the behavioral data and neuroanatomical measures. These sections will discuss the results at each phase of the study, the relevance of the result at one phase to other phases of this project, the anatomical and behavioral specificity of the findings and the hand preference interaction. The exploratory frontal lobe results and the longitudinal findings will be discussed in separate sections.

Kindergarten & 1st Grade Results

Hypotheses 1 & 2 predicted PHRA would be significantly related to kindergarten spelling and 1st grade phonological tasks. These predictions were not supported. Unexpectedly, central sulcus asymmetry (MBA or SBA) did predict kindergarten spelling performance and 1st grade performance n the Woodcock Johnson Tests of Reading

Achievement. There are a number of potential explanations why PHRA was not significant and MBA was significantly related to kindergarten and 1st grade measures.

The most likely reason for the kindergarten and 1st grade results is statistical. If there was simply a relationship of cerebral asymmetry to the kindergarten and 1st grade measures then one would expect both PHRA and MBA to be significant, unless PHRA and MBA had different distributions. The kindergarten and 1st grade measures had restricted ranges because children were only beginning to master reading skills. MBA had a much more restricted range than PHRA. The ranges of MBA and the behavioral tests favored positive results.

The possibility also exists that there was no relationship between kindergarten and 1st grade measures with PHRA or PARA because the anatomical measures were taken 5 years later and did not accurately reflect anatomy during kindergarten. Ideally, a MRI scan would have also been performed in kindergarten and 1st grade. However, there is no direct evidence that gross anatomical structure changes dramatically from kindergarten to 6th grade. Asymmetry of the planum temporale is already present in fetal brains. But it is possible that the range of planar asymmetry is increased with development. Wada (1977) reported that adult brains had qualitatively greater planar asymmetry than fetal brains. This is an important point because the reading skill status of each subject did not change dramatically during elementary school, relative to the other subjects. The biggest change in test scores from kindergarten to 6th grade was the range of performance among the sample. Children who had low scores in kindergarten developed at a slower rate than children with above average kindergarten spelling scores.

6th Grade Results

The neuroanatomical and 6th grade behavioral data demonstrate dramatic relationships that begin to illuminate the role of hand preference, SES and cerebral asymmetry on phonological performance. Predictions about the relationship of PHRA to reading skill were supported. PHRA and other anatomical measures significantly predicted 6th grade reading skill. This section explains the importance of the 6th grade results to the interpretation of the kindergarten and 1st grade data , discusses anatomical and behavioral specificity, and the hand preference interaction.

The impact of anatomy on phonological skill relative to SES

Figure 3-11 demonstrates the two distinct planar asymmetry and reading skill slopes that characterize the high and low SES groups. Children with rightward asymmetry from high SES families performed as well as children with leftward asymmetry from low SES families. Factors related to a high SES seemed to protect children with a rightward asymmetry from the serious risk for reading failure present in children with the same anatomy but a low socioeconomic environment. Every child with above average reading skill had asymmetry appropriate for their hand preference and a family with a high socioeconomic status. It seems that a low socioeconomic environment prevents children with leftward asymmetry from reaching their full potential.

This result is similar to twin studies that demonstrate unique contributions of genetics and environment to IQ (Petrill et al., 1998; Plomin and Thompson, 1993), language (Emde et al., 1992), temperament (Emde et al., 1992), and elementary cognitive tasks (Petrill et al., 1998). The additive effects of environment and genetics is also commonly reported for biological characteristics such as cholesterol (Bodurtha et al., 1991) and blood pressure (Schieken et al., 1989). However, this is the first study to measure variables from both domains. The results suggest that both neuroanatomy and environment are associated with behavioral performance in children.

Surprisingly, there were no significant relationships between measures of cerebral asymmetry and SES. Asymmetry of the planum temporale has been seen in fetal and newborn brains. Although Wada (1977) and Witelson (1973) reported less asymmetry in fetal brains than adults, there has yet to be a study examining whether planar temporale surface area changes across development at the gross anatomical level. However, it is clear that experience and training can alter the size of receptive fields in motivated gerbils, primates, and humans (Merzenich, 1996; Nudo et al., 1996; Karni, Meyer et al., 1995; Pascual-Leone, 1993).

The anatomy of the children from different economic backgrounds may appear very similar at the gross anatomical level, but could be dramatically different at the cellular level. Impoverished environments have profoundly negative influences on synaptic density, dendritic arborization and neuronal survival compared to "enriched environments" in rats (Greenough et al., 1985; Greenough et al. 1986). Although children from different socioeconomic backgrounds may have the same gross asymmetry, due to similarly sized left and right plana, it is possible that their anatomy at the cellular level exhibits markedly different cytoarchitectonics.

There was a difference in the structure-function relationships between SES groups. Planar asymmetry was a stronger predictor of phonological skill among the low SES children. Although correlations between planar asymmetry and phonological performance were significant for both SES groups, they were consistently higher for the low SES groups. The most probable explanation is that high SES children were more likely to ceiling on the behavioral tasks. Restriction of range would reduce the variance and strength of the structure-function correlation.

Alternatively, the high SES children with reversed asymmetry might have been given the opportunity to develop different strategies for solving linguistic problems by establishing a different pattern of neuroanatomical connections, even though they began with the same anatomical baseline potential as the low SES children. And, if planar asymmetry is simply a reflection of overall cerebral asymmetry (see Anatomical Specificity) and reversed asymmetry reflects developmental instability or cerebral malformation, then a supportive environment appears to significantly benefit children burdened with developmental anomalies. These potential scenarios could reduce the structure-function relationships among high SES children and possibly enhance those relationships among low SES children.

Relevance to kindergarten and 1st grade data

The 6th grade results strengthen the interpretation that PHRA was not related to the kindergarten and 1st grade data due to the restricted range of performance. PHRA, MBA, and PARA were all related to 6th grade phonological performance and were redundant. However, PHRA and PARA predicted more variance in phonological performance than MBA because the broader range of these anatomical measures favored positive results with the broader range of the phonological variables.

Anatomical specificity

The results demonstrate that planar asymmetry (horizontal and vertical) and central sulcus asymmetry predict similar variance in reading skill. They reveal that the relationship of brain asymmetry to phonological performance is not specific to auditory association cortex. This suggests that cerebral asymmetry, not just planar asymmetry, is predictive of reading skill.

Amunts et al. (1997) found that right-handed keyboard players exhibited significantly different asymmetry of the precentral gyrus than normal right-handed controls. The professional musicians had exaggerated leftward asymmetry. The regions of the central sulcus that produced the hand preference effect were the most dorsal sections where the lower extremities are more likely to be represented. There were no data reported to show the effect was not present in some other dorsal region. Therefore the effect may be related to keyboard training or genetic musical ability but not specifically to the precentral gyrus.

Foundas has reported asymmetry of the pars triangularis and planum temporale are related to hand preference and hemispheric dominance for language. This suggests that asymmetry of the planum temporale and pars triangularis are related to hand preference and language dominance due to some indirect developmental mechanism. If this study had been able to achieve reliability using the Foundas method of measuring the pars triangularis, it is possible that the pars triangularis would also be related to behavior.

Future studies should consider measures of frontal and occipital petalia as indices of non-specific brain asymmetry.

Behavioral specificity to anatomy

The results section demonstrated that there was behavioral specificity for verbal tasks. FSIQ, motor and visuospatial tasks were not related to planar asymmetry. However, phonological awareness was not the only task for which performance was associated with planar asymmetry. The Information and Similarities verbal IQ subtests were also related to planar asymmetry. FSIQ was probably not significantly related to planar asymmetry because of the Block Design (visuo-spatial task) contribution to the variable. This suggests that planar asymmetry is more strongly related to a verbal factor than to "g" or general intelligence because all 3 subtests (Block Design, Information, & Similarities) are all heavily "g" loaded. This conclusion is partially supported by the Rumsey et al (1997) study that reported planar asymmetry was related to performance on measures of verbal IQ and phonological tasks in right-handed male controls. The controls were given a short form of the WAIS, but the authors did not report if any spatial tasks were related to planar asymmetry.

Hand preference

Performance on reading skill tests improved as planum temporale asymmetry became increasingly leftward in right-handed children. Leftward asymmetry was related to a strong awareness of speech sounds and rightward asymmetry was related to poor awareness of speech sounds in right-handed children. If a child was non-right-handed then the brain asymmetry and reading skill relationship was reversed. Non-right-handed children with rightward asymmetry had superior reading skills compared to NRH children with leftward asymmetry. Therefore, reading skill performance was dependent on the relationship between the direction of hand preference and brain asymmetry.

The interaction effect between handedness and planar asymmetry explains some of the findings that predict planar asymmetry. Hand preference and oral language impairment are consistently reported to be related to reversed cerebral asymmetry. Non-right-handed subjects with normal oral language and right-handed subjects with oral language impairment are more likely to exhibit symmetry or reversed asymmetry. These findings seem contradictory or at least confusing until one recognizes that both the direction of cerebral asymmetry and hand preference are important in predicting oral language performance. Figure 4-1 presents a testable model of the congruent asymmetry relationship to oral language performance.

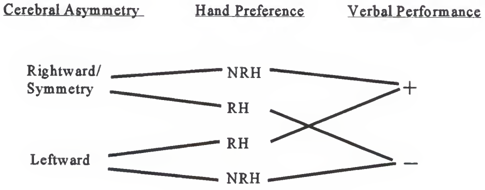


Figure 4-1. A Path Model of Congruent Asymmetry

There is support for the concept of crossed or congruent asymmetry. Kertesz et al. (1992) examined the relationship of laterality for dichotic listening and visual half field presentation to gross anatomical measures in 52 right-handed and 52 left-handed adults. The direction of both hand preference and functional laterality were related to the anatomical measures. "*Subjects in whom the same hemisphere is dominant for both handedness and language* (according to dichotic listening) *have larger structures than those in whom dominance is crossed.*" (p. 601). Unfortunately, Kertesz et al. (1992) did not report the relationship of brain asymmetry to behavior.

There are also behavioral data to support the congruent asymmetry finding. Hernandez et al. (1997) sought to determine if the direction of hand preference and language laterality influenced reading performance. Language lateralization was defined using a dichotic listening task. Individuals with a right ear advantage were categorized as having left hemisphere language and those with a left ear advantage were categorized as having right hemisphere language localization. Performance was reported to be better on reading comprehension, efficiency, accuracy and speed tasks when language lateralization and hand preference were convergent (Left Ear Advantage and right-hand preference or Right Ear Advantage and left-hand preference).

The hand preference and cerebral asymmetry findings raise the question as to why congruent asymmetry might facilitate oral language. The answer could relate to the concurrent development of handedness and language. Bates et al. (1986) have reported that children cycle in and out of a stable expression for hand preference around the same time they are trying to solve new problems in language development. For example, hand preference is less stable between 7 and 9 months when infants are beginning to babble in syllables; at 12-14 months when children are learning their first words; and at 20 months when they are putting words together in sentences. Bates et al. (1986) show that 13 and 18 month old infants are more likely have a RH preference for pointing than any other manual activity. In addition, children expressed a greater RH preference during symbolic play compared to non-symbolic actions.

Studies employing a transcranial magnetic stimulation (TMS) paradigm to study motor control provide more evidence that hand preference and oral language are associated. EMG recordings of hand and arm muscle showed increased activation of the preferred hand when subjects read aloud (Tokimura et al., 1996). In right-handed subjects there is increased activation in the right hand muscles when the left hemisphere motor cortex receives TMS during overt reading. There was no effect when subjects read silently or made sounds without speaking. In addition, there was not increased activation in the left hand during reading aloud and right hemisphere stimulation. This effect was reversed for left handed subjects. Reading aloud elicited increased activation of left, not right, hand muscles.

The TMS paradigm might provide a means of investigating congruent asymmetry. If hand preference and the direction of cerebral asymmetry facilitate verbal ability, then subjects with congruent asymmetry should exhibit increased muscle activation for the dominant hand when reading aloud. Subjects with incongruent asymmetry would not be predicted to show an increase in activation. The congruent and incongruent groups should include subjects with dominant left or right-hand preference in order to increase the power of the study and specificity of the findings.

Exploratory Inferior Frontal Gyrus Results

The inferior frontal gyrus was measured for two reasons: 1) to assess the specificity of the relationship between planar asymmetry and reading development; and 2) to perform exploratory analyses of the relationship between the inferior frontal gyrus to oral fluency and speech production tasks. The inferior frontal gyrus measurement was defined on the basis of functional imaging evidence for regional activation during naming and fluency tasks.

It is reasonable to assume that the architecture of the IFG is related to naming and fluency because of its role in speech and activation during functional imaging language tasks. Anatomical measures of the frontal lobe have been related to language. Foundas (1995) found pars triangularis asymmetry was related to hemispheric dominance for language. Gauger et al. (1997) found significant differences in the surface area of the pars triangularis between children with specific language impairment and normal children. And Clark and Plante (1998) reported that an extra sulcus in the inferior frontal gyrus was associated with developmental language disorder in 21 parents of children with developmental language disorder and 20 control adults.

The exploratory IFG analyses did reveal a significant relationship between IFG category fluency. This relationship was due to the size of the right IFG. Right-handed children with a large right IFG could name more animals or vegetables in a minute.

The IFG and category fluency relationship is consistent with a general effect of brain asymmetry on verbal performance. The frontal lobe typically exhibits a right frontal petalia (Zilles et al., 1996). Extreme caution should be used when interpreting the results. Given the number of correlations that were run, it is quite possible that some of the relationships are spurious and would not withstand replication.

The Extra Sulcus. The measurement used in this study differed from the Foundas method, for theoretical and practical reasons. The region of measurement was based on functional imaging studies. However, instead of measuring only the pars triangularis, the measurements of the pars triangularis and pars opercularis was combined in order to obtain reliability. Reliability for only the pars triangularis could not be achieved.

The extra sulcus identified by Clark and Plante could explain the difficulty in obtaining reliability. An extra sulcus would increase error variability in measurements by making boundaries ambiguous. To investigate the possibility that a qualitative assessment of the IFG might identify children language impairment. The Clark & Plante (1998) inferior frontal gyrus classification system was used to assess the frontal lobe morphology of children in this study. There was a trend suggesting that an extra sulcus was more predictive of phonological deficits, than naming or production deficits. This is preliminary data that should be replicated.

Change in Reading Performance from Kindergarten to 6th Grade

The 6th grade anatomical and phonological data confirmed the prediction that planar asymmetry would be associated with phonological awareness. Following from this prediction, a second prediction was made that planar asymmetry would be related to the development of phonological skill between kindergarten and 6th grade. This prediction was also confirmed. Regardless of income level, RH children with leftward asymmetry developed phonological skills at a faster rate than children with symmetry or reversed planar asymmetry.

Developmental reading groups

The within sample ranking of children's phonological performance from kindergarten to 6th grade was stable. There was very little movement across below average, average and superior phonological skill reading groups between kindergarten and 6th grade. This consistency in group performance during the elementary school years made it possible to group children into below average, average and superior phonological skill groups (see Results for description of classification criteria).

A comparison of planar asymmetry between the right-handed below average group to average and superior reading group revealed a significant difference in planar asymmetry. The average and superior phonological group had significantly greater leftward asymmetry compared to the below average group. Children with leftward asymmetry had at least average phonological skill from kindergarten to 6th grade.

Leftward asymmetry appears to provide an advantage for the development of phonological skill.

The data once again demonstrate the importance of controlling for hand preference in neuroanatomical studies. Including the NRH children in the reading group planar asymmetry comparison eliminated the difference in asymmetry between the groups because NRH children with above or superior reading skill performance across development had reversed asymmetry (i.e. rightward asymmetry). Asymmetry comparisons could not be made with regard to developmental reading groups among the NRH subjects because there was only 1 NRH child in the below average developmental reading group.

Rate of phonological skill development

This section has thus far discussed the relationship of planar asymmetry to oral language performance, and specifically to performance at each phase of the study. An examination of phonological skill development can also address the rate of acquisition. The growth rate of phonological skill provided an indication as to whether some children developed reading skill more quickly than others, regardless of initial performance.

The rate of phonological skill acquisition was related to planar asymmetry in RH children. Children with leftward asymmetry made greater gains in reading skill than children with reversed asymmetry. This is additional evidence to suggest that leftward asymmetry provides a developmental advantage for acquiring linguistic skills.

The rate of development effect was irrespective of SES. Children from low SES homes developed at the same rate as children from high SES homes if they had similar asymmetry. However, at any given time the performance of a low SES child was below that of a high SES child with the same anatomy. This result, coupled with knowledge about the language environment of low SES homes, implies that the high SES children started phonological training (informal or formal) earlier in development. Parents of low SES and high SES children are reported to exhibit different styles of interacting with their children. High SES parents could expose their children to stimuli that would facilitate their phonological development at an earlier age than the low SES children.

Direction of the longitudinal relationship. The longitudinal data raise the question as to whether planar asymmetry leads to a faster acquisition of phonological skill, whether asymmetry changes as a consequence phonological development, or planar asymmetry is indirectly correlated with phonological development. Again, it is unfortunate that anatomical data was not available from the kindergarten or first grade phases of the study. Future studies will provide evidence of how much and if change occurs in brain asymmetry through development during the primary school years. However, until those studies are completed one can only speculate about the direction of influence between planar asymmetry and reading development. Based on the available literature, the prediction could be made that planar asymmetry has an early influence on the ease with which phonological skill is acquired and this leads to a more exaggerated asymmetry through development as phonological skills are acquired.

Gallagher and Watkin (1997) used ultrasound to examine the brain development of 4 fetuses. 3 of the fetuses were progeny of parents with normal language ability and 1 was from a family with a history of language impairment. The fetus with a family history of language impairment had limited growth of the left inferior cortex (primarily temporal lobe) and more right hemisphere growth between 28 and 32 weeks of gestation compared with the other 3 fetuses. The other 3 fetuses exhibited more left hemisphere growth and minimal change in the right hemisphere. Although it is not certain that the affected child will develop language impairment or a non-right-hand preference, the data suggest that there are individual differences in the patterns of early brain development that lead to individual differences in brain asymmetry seen in adults or children.

Brain asymmetries might be established during gestation, but it is not clear whether or how those asymmetries could change across the life span. Wada (1977) compared the planar asymmetry of fetal and adult brains. While both groups exhibited asymmetry, the adults exhibited qualitatively more asymmetry than was present in the fetal brains. In the Leonard et al. (1996) study the youngest children tended to have large right plana and poor phonological skill. Children's poor phonological skill could have been the result of reduced asymmetry because of the large right planum, or the right planum of these children could decrease in size with the development of their phonological skills. Leonard et al. (1996), Rumsey et al. (1997), and this study of children from the same age cohort have each demonstrated the right planum was predictive of phonological skill. Planar asymmetry could become exaggerated during phonological development as a result of pruning in the right hemisphere.

A Role for the Right Hemisphere

Environmental sound exposure during gestation could initiate the process of specializing neural circuits for processing speech sounds. A fetus can identify the intensity and frequency of sound by the third trimester (LeCauet, 1995). However, the process of establishing phonological boundaries for the representation of speech sounds occurs between 6 months and a year (Shafer et al., 1998). Children can perceive the phonological units of any language in the world at 6 months, but by a year they have specific and strong representations for native speech sounds (Kuhl et al., 1997).

Prenatal exposure to auditory stimuli and postnatal motherese are believed to be important to a child's acquisition of language. Motherese is a broad or stretched presentation of vowel sounds performed by mothers across the world when communicating to their infants (Fernald, 1989; Kuhl et al., 1997). These sounds provide specific information about the speech sound units that form the structure of oral language. Fernald (1993) hypothesizes that infants need to understand the intonation provided by motherese before they can understand language. She supported this hypothesis by showing that children learned the meanings of words said in motherese more rapidly than words said in typical adult speech (Fernald, 1989).

Processing motherese, speech prosody or melody have been proposed to be performed by the right hemisphere. Listening to happy and sad speech elicits posterior right hemisphere activation as measured by EEG (Pihan et al., 1997). And listening to melodies increases activation (by rCBF) in the right superior temporal gyrus (Zatorre et al., 1994).

Infant's preference for motherese over adult typical speech (Cooper and Aslin, 1994) and the activation of the right hemisphere by speech prosody and melodic tasks would suggest that the right hemisphere is important in early language development. This hypothesis is corroborated by Bates et al. (1995) and Reilly et al. (1995) who report that focal posterior right hemisphere damage within six months of postnatal life leads to language comprehension and grammatical impairments later in childhood.

The Bates et al. (1995) study suggests that the right hemisphere is important for successful language acquisition. There is also evidence to suggest that the right hemisphere is involved in some aspects of oral language performance. Adults that acquire dyslexia as a result of a cerebral accident to the left hemisphere are still capable of oral reading of high imagability and concrete words such as nouns, but not functor words (Coslett et al., 1993). This finding suggests that the right hemisphere can perform language tasks.

Confirmation of right hemisphere involvement in reading has been shown using TMS. TMS of the right temporo-parietal area inhibits oral reading of nouns in cases of adult acquired dyslexia (Coslett et al., 1993). Hemispheric reorganization could have occurred in the adult dyslexics as it does in children who recover language after a left hemispherectomy (Satz et al., 1988). However, the role of the right hemisphere in normal language organization is supported by studies of split brain patients who can match printed words that are presented to the left visual field with the matching objects (Zaidel, 1981).

In summary, planar asymmetry at 11 years of age is related to the performance and rate of reading skill development between kindergarten and 6th grade. However, it is not clear that cerebral asymmetry changes and coincides with the acquisition of literacy or that cerebral asymmetry is stable and represents a child's potential for developing reading and language skills. The answer is most likely some combination of both explanations. Determining the correct answer can only be achieved by longitudinal imaging studies that carefully assess environmental variables through the course of the study.

A Comparison to Previous Planar Asymmetry Studies

The use of different imaging protocols used to scan brains in neuroimaging studies makes the synthesis of results from these studies an arduous task. The different protocols produce images of different thickness, have different signal to noise ratio, and format images in different planes of section. Each of these differences in protocol can produce error variability in measurement. A second problem occurs from the use of different methods to define neuroanatomical regions, which are given the same name. For these reasons, comparison of this study to other published studies will emphasize those that have used similar methodology.

The size of the left and right plana, and the asymmetry of the planum were nearly identical to the measures of normal control children in the Gauger et al. (1997) and

Leonard et al. (1996) studies. The left and right surface areas of the planum were also similar to adult controls and dyslexics in the Leonard et al. (1993) study that found no difference in the planum temporale between dyslexics and controls.

The Leonard et al. (1998) replication of the Leonard et al. (1993) dyslexia study also yielded planar measures that were similar to the results of this study. However, the asymmetry was slightly more exaggerated among the adult dyslexics and controls. This exaggerated asymmetry was due to a moderately smaller right planum. These MRI data corroborate Wada's post-mortem report that planar asymmetry is more extreme in adults than fetal brains.

The relationship between the size and asymmetry of the planum temporale to verbal and phonological skill is also consistent with the findings from studies examining this relationship among children (Leonard et al., 1996; Semrud-Clikeman 1990) and adults (Rumsey et al., 1997). Phonological or verbal performance improved as planar asymmetry became increasingly leftward among the right-handed subjects in each study. And in each study, the right hemisphere planum seems to contribute most to the structure-function relationship. Smaller right plana are related to better verbal or phonological performance among right-handed subjects.

The Non-Right-Handed Effect

Numerous studies have shown less or reversed cerebral asymmetry among normal NRH. The cerebral asymmetries that have been associated with handedness include frontal and occipital petalia, pars triangularis, central sulcus and the planum temporale.

In this study and Leonard et al. (1996) there was no hand preference group difference in planar asymmetry.

Previous studies demonstrating significantly reversed cerebral asymmetry in NRH have included "super" normal subjects. "Super" normal subjects could include university faculty (Foundas et al, 1995) and college students (Steinmetz et al., 1995). The present study of a representative community sample has found that children with a non-right-hand preference performed better if they had rightward asymmetry or symmetry of the planum. If the normal left handed controls in an imaging study have superior verbal and phonological skills, then one would expect a greater likelihood of reversed planar asymmetry and a greater chance of a handedness group difference in asymmetry. Many neuroimaging laboratories could perform retrospective studies to test this hypothesis.

If functional laterality and anatomical asymmetry were completely reversed in NRH subjects, then one would predict that the left planum would be a stronger predictor of the asymmetry and reading skill. However, evidence from the WADA, dichotic listening, and visual half field presentation show that most left handed people have a left hemisphere advantage for these language laterality tasks (Rasmussen and Milner, 1977). Therefore it is reasonable to assume that NRH do not have a completely reversed functional and anatomical asymmetry from RH subjects, but that they have a different functional and anatomical organization that processes receptive oral language differently.

The data from this study suggest that reversed asymmetry is not necessarily indicative of language impairment. Language impairment may not occur unless the organization of language is incongruent with the organization of other functions such as hand preference. For instance, reorganization of function following brain injury in children often leads to the preservation of language at the expense of other cognitive skills (Satz et al., 1990).

The planar asymmetry results are consistent with previous studies. The right planum in right and non-right-handed subjects was critical in predicting reading skill. Future attempts toward understanding the relationship of planar asymmetry to oral language and verbal skill should address the role of the "non-dominant" right hemisphere.

Oral Language Impairment vs. Dyslexia

Chapter one made a distinction between oral language impairment and dyslexia based on differences in the behavioral and anatomical profile of the two groups. Behaviorally, dyslexic and oral language-impaired individuals both have a phonological deficit, but oral language impairment is accompanied by additional comprehension and/or production deficits. The comprehension and production deficits are often at the expense of verbal IQ. Neuroanatomically, there is more consistency in findings of planar asymmetry differences in the brains of oral language impaired subjects compared to normals, than there is for dyslexics. This study provides support for the notion that the planar asymmetry relationship to phonology is influenced by verbal ability or oral language.

Planar asymmetry, phonological skill, and measures of verbal IQ were all interrelated. There were only 3 subjects with a dyslexic profile whose phonological skill was not predicted by their verbal IQ. These three subjects had phonological skill that was worse than expected given their planar asymmetry and their high SES. Their data fell in the slope of the low SES children. These data provide support for the idea that two disorders like specific language impairment and dyslexia can have similar symptoms (phonological impairment), but different underlying neurobiological explanations for the symptoms.

Nature and Nurture Contributions to Reading Development

Perhaps the most important finding to emerge from this dissertation was that both SES and brain structure provide independent contributions to a child's reading skill. Children could attain reading skills within the normal range regardless of their anatomy if they were from high SES environment, or if they were from a low SES family and had normal asymmetry. However, a child with both reversed asymmetry and a low SES environment was at serious risk for reading problems, while a high SES and congruent asymmetry appeared to provide children with a developmental advantage for reading skill acquisition (and probably verbal success). This is the first neuroimaging study to account for both the effects of brain structure and the environment and show how they both contribute to reading skill development.

Individual Differences

This study was designed to examine individual differences. The public school sample of children also made it possible to examine how both anatomy and environment contributed to any differences in performance. There are no other imaging studies that have examined both anatomy and environment. Only twin studies of language development have attempted to address the combined effect of nature and nurture and none to date has examined the contribution of anatomy.

Dale et al. (1998) attempted to model the effects of nature and nurture on early language development in twins. They distinguished between individual differences in language development and language delay on the basis of heredity. In an epidemiological sample of 3000 twins, children in the bottom 5% of the sample exhibited a much stronger heritability for vocabulary production compared to children in the average range or above for whom a shared twin environment was a more important factor. Planar measurements should be make in a sample obtained from this study.

In the present study, individual differences were predicted by hand preference, brain asymmetry, the interaction between brain asymmetry and hand preference, and SES. SES and planar asymmetry each accounted for a little more than a third of unique variance in reading skill. Together, the hand preference, planar asymmetry, and hand preference-planar asymmetry interaction variables accounted for the majority of the variance in reading skill. These results are difficult to compare to the Dale study because of the different designs and sample sizes. The Dale study was of heredity and shared environments, not specific biological variables and the environment. SES and genetics are inextricably entangled in this study because the home environment could be a created by parental genetics to some extent. In addition, factors related to SES and other environmental variables (external, maternal effects, teratogens, etc...) could interact with genes to influence hand preference and brain asymmetry.

Fetal alcohol syndrome (FAS) is one example of teratogenic effects on development. A number of behavioral and physical abnormalities result from FAS. Hearing disorder is a common problem among children prenatally exposed to alcohol. Different forms of hearing disorder associated with FAS include delay in auditory development, sensorineural hearing loss, conductive hearing loss due to otitis media, and central hearing loss. Each of these auditory complications can lead to language impairment, a problem that is prevalent among FAS children. (Church and Kaltenbach, 1997).

The development of the chick visual system is example of how the environment can influence anatomy. Asymmetrical development of visual projections from the thalamus to the forebrain of a chick are dependent on exposure to light just prior to hatching and circulating levels of testosterone. An increase in testosterone levels reverses asymmetry in males and to a lesser extent in females (Schwarz and Rogers, 1992). This finding is support for the Geschwind, Behan & Galaburda (1985) theory that high levels of prenatal testosterone could alter cerebral asymmetry. The theory also proposes that high levels of testosterone would lead to altered cerebral dominance, language impairment, and immune disorders.

Through prenatal or early developmental influences, additional effects of environment on reading skill could be expressed as variance attributed to biological variables such as hand preference or cerebral asymmetry. Although it is not clear that environmental factors influence brain asymmetry, impoverished environments have been known to influence rat neural architecture since the 1960's (Diamond et al., 1966;

Greenough et al., 1986). The contribution of the main effects and interactions between nature and nurture to predicting reading skill will not be known until there is a clear understanding of the neurobiological mechanisms influencing hand preference and brain asymmetry.

Molecular genetics research is only beginning to examine human behavioral questions. Dyslexia, phonological decoding, hand preference, and IQ have all been linked to the HLA region of chromosome 6 (Cardon et al., 1995; Grigorenko et al., 1997; Gangestad et al., 1996; Petrill et al., 1996). Among behaviors in which there is a great degree of variability attributable to environmental variables, there may be difficulty finding genetic linkage for behavioral phenotypes. A more fruitful approach is to examine linkage to the neurobiological variables that mediate the behavioral phenotype of interest. For example, a functional imaging study of dyslexics demonstrated that the variability in activation during phonological tasks was more strongly related to genetic linkage results than the diagnosis of dyslexia (Wood, 1997).

The normal distribution of cerebral asymmetry suggests that the development of cerebral asymmetry is due to additive genetic effects. In addition to the HLA region, a mutant situs inversus gene (Levin, 1997), or chromosome regions 7p and 22q11 could be involved in the development of asymmetry. Regions 7p and 22q11 have both been implicated in chromosomal abnormalities that lead to enlarged sylvian fissures (Bingham, 1997) and brain asymmetry (Lurie, 1995). Support for the premise of additive effects on cerebral asymmetry is found in a study showing variation in retinal ganglion cell number in mice is linked to a major quantitative trait loci on chromosome 11 (Williams et al., 1998).

The direction of planar asymmetry is reported to be heritable (Jackson and Plante, 1996). Therefore it might be possible to establish family pedigrees for the mode of planar asymmetry inheritance. Linkage studies targeting the HLA region and the other proposed linkage sites could begin to clarify the hand preference, cerebral asymmetry and oral language relationships.

Race and SES

A challenge to the interpretation that the socioeconomic environment has a main effect on reading development could be raised due to the differing distribution of Caucasian and African American subjects in the two SES groups. As in other samples, the majority of low SES children were African American and the majority of high SES children were Caucasian. Although the sample is representative of Alachua County, Fl., it is not balanced according to race. Therefore any effects of SES could be viewed as a race effect. However, multiple regression demonstrated that SES was a better predictor of reading skill than race. Put more simply, there were Caucasian children who were low SES that had poor reading skills and high SES African American subjects who had average to above average reading skills. The findings suggest that poverty and its associated stresses play a larger role in language environment than race.

Summary

There is not a clear answer as to how the environment might interact with genetics to produce hand preference and brain asymmetry. However, the results from this dissertation demonstrate that both the socioeconomic environment and biological attributes affect the development of reading skill. The basic message is that an environment that encourages reading success can help to neutralize the potentially negative effects of a brain that does not have the optimal organization for learning to read.

Technical & Methodological Considerations

There were a few technical concerns that limit the interpretation of data from this study. These problems include issues related to the psychometric properties of the data, missing data, and an unbalanced sample that resulted from this quasi-epidemiological study. Despite these problems, this study yielded a number of important findings.

Psychometrics. There were psychometric problems with some of the anatomical and behavioral data. Specifically, restricted ranges influenced the results of some analyses. With respect to the behavioral variables, children were beginning to ceiling on the 6th grade Woodcock-Johnson tasks. Although children's performance on all tasks was considerably more variability among the 6th grade variables, this potential range of performance was truncated because some tests were not challenging enough.

Their was a similar problem with the anatomical variables. MBA and PHRA each exhibited different ranges that influenced their relationship to the behavioral variables.

The planum temporale exhibits a large hemispheric asymmetry in the brain (Leonard, 1996) and can therefore produce a broad range of asymmetries. In addition, the measurement technique used in this study examined the region of the planum that exhibits the greatest degree of asymmetry (Leonard et al, 1998). In contrast, only the region of the motor and sensory banks that approximates the region for hand representation was measured. The total area in each hemispheric measurement of the central sulcus is much smaller than that for the horizontal or ascending rami of the planum temporale. This is an example of how the selection of measurement techniques influence data characteristics and the results of multivariate analyses.

Missing Data. There were almost no cases of missing data for phase III of the study. However, eleven of the children that participated in phases I and III of this study, did not participate in phase II of this project. This significant drop in phase II sample size prevented direct comparisons of the 1st and 6th grade performances on the Woodcock-Johnson tests of reading achievement.

Sample Selection. The design of this study resulted in an unbalanced sample. It was impossible to control for the hand preference of subjects. A disproportionate number of children from high SES families exhibited a non-right-hand preference. A sample size of only 39 makes it nearly impossible to speculate about the causes or meaning of the aggregation of non-right-handed subjects in the high SES group. This study needs replication to verify the congruent asymmetry effect in the high SES group and establish if there is such an effect for children from low SES families.

General Summary

This study has confirmed the findings of previous neuroimaging studies. Cerebral asymmetry was related to phonological skill and verbal ability. Understanding of the cerebral asymmetry and reading skill relationship has been advanced by the demonstration that the direction of hand preference and cerebral asymmetry are both important in predicting oral language performance. Another critical factor related to oral language performance was socioeconomic status. This finding is compelling because planar asymmetry was related to the rate of reading development between kindergarten and 6th grade. Children with cerebral asymmetry that is incongruent to their hand preference need extra time and support to establish functional reading skills. Children without congruent asymmetry and a proper developmental environment are at particular risk for reading impairment.

APPENDIX A
PARENT INFORMATION LETTER

Dear Parents,

Thank you for taking the time to consider your child's participation in a very important study on reading development. I spoke with you on the phone. My name is Mark Eckert. I am a graduate student in the Psychology department at the University of Florida *(or insert name of caller)*. I am working under the direct supervision of Dr. Christiana Leonard, a professor of neuroscience, and Dr. Linda Lombardino, a professor of speech pathology.

In 1992, your child was involved in a research project conducted by Dr. Lombardino. In the first part of this project he/she was tested for his/her pre-reading skills . A year later, some of these same children were tested to see how good they were at reading. This study showed that children who had a good awareness of speech sounds before learning to read were reading better than children who did have a good awareness of speech sounds.

It is now 3 years later and we want to see how the children's reading skills are developing and whether structures in the language areas of their brain are related to this development. We have been funded by the NIH to study the long term language development of children. This study might provide information on which children are at risk for developing reading problems and which children are likely to benefit most from extra help in learning to read.

Our research over the past three years has included over 100 children from the Gainesville area. This research shows that specific language skills are related to the size and shape of brain regions associated with processing sounds. This study will be very important because it will allow us to know how the children's reading skills have changed across development and how that change is related to the language areas.

Research Plan

If you give consent, we plan to test the children on a few language and reading skills, basic motor skills and give them a hearing test. The testing will take about an hour. This testing can take place in your home if there is an area in the house that is quiet or at the U.F. Health Center at Shands Hospital.

We also plan to take a picture of the children's brains with MRI. This will take about a ½ hour. A parent can stay in the room with the child while the picture is taken. The scans are done under our direct supervision in a small, comfortable building at the Veterans's Administration hospital. Magnetic Resonance Imaging (MRI) is a sophisticated medical technology that uses a magnetic field and radio waves to create a picture of the inner workings of the body. No radiation is involved.

The two phases of this study will be scheduled at your convenience. The MRI is usually done on Saturdays. However, we can also schedule the MRI on the weekday if that is better for you.

Issues on Risk Factors

There are no known risk factors associated with MRI. The children will be able to watch other children going through the procedure so that they will be familiar with the process before they participate. No pain is involved in this procedure. The MRI does produce a steady hammer sound, so all children wear earplugs and are told about the noise.

Benefits for Children

Children will be given a T-shirt with a picture of a brain, and sent a computer image picture of their own brain scan. All children will also receive $10/hr. for the testing and $20 for the MRI. Although we make every attempt to process payment in a timely manner, there is sometimes a delay of 6 to 8 weeks before the checks are received. The computer pictures of the children's brains will be sent out within 6 weeks following the scan. Payment will be made once all procedures have been completed.

Arrangement for Participation

If your child is interested (or not interested) in participating in this project, please call ***Mark Eckert*** or ***Wendy Swearingin*** at 846-2464 between the hours of 9am to 5pm. Mark can also be reached at 336-6174 after 5pm.

We hope that you will consider working with us on this important project and we appreciate your time in reading this document. Mark Eckert will be contacting you within a couple of weeks to make sure you received this letter.

Sincerely yours,

Mark Eckert
Dept. of Psychology
College of Liberal Arts & Sciences
University of Florida
846-2464
Mark@xray.ufl.edu

Christiana Leonard, Ph.D.
Professor of Neuroscience
Dept. of Neuroscience
College of Medicine
University of Florida
392-4518

Linda J. Lombardino, Ph.D.
Professor of Speech-Language Pathology
Dept. of Communication Processes & Dis.
College of Liberal Arts & Sciences
University of Florida
392-2041

APPENDIX B
INCOME LEVELS FOR SCHOOL LUNCH

B-1. 1997-1998 School Year Scale for Annual Income Lunch Subsidy Qualification.

	Reduced	Free
Family of 1	14,597	10,257
Family of 2	19,654	13,810
Family of 3	24,705	17,359
Family of 4	29,747	20,903
Family of 5	34,779	24,439
Family of 6	39,804	27,970
Family of 7	44,819	31,494
Family of 8	49,821	35,009

APPENDIX C
RESULTS DATA

C-1. Phase I Descriptive Statistics for the Early Reading Screening Inventory Subtests and Total Score.

Test	N	Min.	Max.	Mean	Std. Dev.
Alphabet	39	2.90	10.00	8.3949	2.0342
Spelling	39	.00	8.80	4.6718	2.9521
Reading	39	.00	9.00	2.0128	2.4535
Word Recognition	39	1.30	10.00	6.5179	3.0911
ERSI total score	39	4.20	37.10	21.5974	9.2415

C-2. Phase II Woodcock-Johnson Tests of Achievement (raw scores) Descriptive Statistics

Test	N	Min.	Max.	Mean	Std. Dev.
Word Attack	28	.00	24.00	8.8929	7.7044
Passage Comprehension	28	.00	28.00	13.6071	8.2836
Word Identification	28	1.00	50.00	29.6071	12.9281

C-3. Phase III Behavioral Test Descriptive Statistics.

Test	N	Min.	Max.	Mean	Std.Dev.
Word Attack (rs)	39	4.00	29.00	19.69	6.92
Word Attack (ss)	39	70.00	143.00	104.59	18.41
Word Identification (rs)	39	30.00	56.00	45.03	6.34
Word Identification (ss)	39	73.00	165.00	109.18	19.54

C-3 Continued					
Passage Comprehension (rs)	39	15.00	35.00	25.97	5.01
Passage Comprehension (ss)	39	73.00	136.00	104.23	15.42
Torgesson's Phoneme Reversal	39	1.00	16.00	8.18	4.17
LACT	37	45.00	94.00	70.30	15.38
Memory for Digits (forward)	39	7.00	19.00	12.71	2.78
WISC-FSIQ (Triad)	39	70.00	146.00	103.18	18.50
WISC-Block Design (rs)	39	16.00	64.00	39.92	12.23
WISC-Block Design (ss)	39	3.00	19.00	10.56	3.67
WISC-Information (rs)	39	9.00	27.00	16.18	4.10
WISC-Information (ss)	39	3.00	19.00	9.79	3.48
WISC-Similarities (rs)	39	7.00	30.00	19.21	5.74
WISC-Similarities (ss)	39	2.00	19.00	11.23	3.72
RAN-colors	39	26.25	57.89	37.13	7.34
RAN-letters	39	16.93	37.59	24.76	5.07
RAN-numbers	39	16.59	37.59	23.26	4.65
Controlled Oral Word Association (Categories)	39	16.00	44.00	31.49	6.78
Controlled Oral Word Association (Letters-FAS)	39	14.00	43.00	26.10	7.07
Quantitative Handedness	37	-1.00	1.00	.70	.46
Left Hand Peg Board Avg.	38	10.00	17.00	12.96	1.48
Left Hand Dynamometer Avg.	39	12.00	31.00	20.37	3.94
Right-Hand Peg Board Avg.	38	10.50	16.50	13.76	1.55
Right-Hand Dynamometer Avg.	39	14.50	31.00	22.21	3.89

C-4. Phase III Neuroanatomical Data Descriptive Statistics

Test	N	Minimum	Maximum	Mean	Std. Dev.
Total Brain Volume	39	899.10	1425.10	1166.69	120.16
Brain Volume Asymmetry	39	-14.20	15.40	-.32	6.32
Left Hemisphere Volume	39	436.40	710.10	582.16	60.04
Right Hemisphere Volume	39	462.70	715.00	584.55	65.23
Left PAR	39	.08	3.51	1.41	.89
Left PDR	39	.05	1.11	.28	.26
Left PHR	39	.91	5.04	3.14	1.11
Right PAR	39	.12	4.77	1.86	1.06
Right PDR	39	.04	1.41	.32	.31
Right PHR	39	.35	4.31	2.24	1.04
PHR Asymmetry	39	-.86	1.32	.36	.57
Left Motor Bank	39	4.68	9.38	6.88	.99
Right Motor Bank	39	5.48	8.70	6.89	.85
Motor Bank Asymmetry	39	-.39	.26	-.01	.15
Left Sensory Bank	39	5.20	10.17	7.07	.99
Right Sensory Bank	39	5.66	8.92	6.95	.84
Sensory Bank Asymmetry	39	-.26	.30	.01	.13

C-4 Continued

Left Olfactory Sulcus	38	3.35	9.43	6.40	1.61
Right Olfactory Sulcus	38	3.37	10.12	6.83	1.58
Olfactory Sulcus Asymmetry	38	-.63	.22	-.06	.18
Left IFG	39	3.21	11.94	6.92	1.70
Right IFG	39	3.82	11.28	6.65	1.49
IFG Asymmetry	39	-.36	.41	.03	.19

C-5. Lunch Subsidy Status Correlation with Behavioral Assessment

Test	Pearson R	P Value
ERSI total score	-0.4968	0.008
ERSI-Spelling subtest	-0.59162	0.001
WJ-Word Attack raw score phase 2	-0.46351	0.034
WJ-Word ID raw score phase 2	-0.4588	0.036
WJ-Passage Comp. raw score phase 2	-0.497	0.022
WJ- Word Attack raw score	-0.49599	0.009
WJ- Word Attack standard score phase 3	-0.4344	0.024
WJ-Word Identification raw score	-0.55771	0.003
WJ- Word ID standard score phase 3	-0.58948	0.001
WJ-Passage Comp raw score phase 3	-0.78118	0.00001
WJ-Passage Comprehension standard score phase 3	-0.69967	0.0004
Lindamood Auditory Conceptualization Task	-0.68135	0.0002
Torgesson Phoneme Reversal	-0.64245	0.0003
Torgesson Memory for Digits (forward)	-0.16021	0.424
FSIQ-Info, Similiarities, Block Des. Triad	-0.74852	0.00001
Rapid Automatic Naming-Colors	0.211027	0.291
Rapid Automatic Naming- Letters	0.156508	0.436
Rapid Automatic Naming-Numbers	0.063795	0.752
fluency (category word generation)	-0.58595	0.001
fluency (word generation to letters)	-0.18052	0.368

C-6. Significant Correlations between Neuroanatomical Measures and Lunch Status Among Children With a Right-Hand Preference.

Neuroanatomical Measures	Pearson R	P Value
IFG Asymmetry	.201	.315
Left IFG	-.292	.139
Right IFG	**-.398**	**.040**
Left PAR	.243	.222
Left PDR	-.030	.882
Left PHR	-.136	.499
Right PAR	.047	.819
Right PDR	-.112	.580
Right PHR	-.020	.920
PHR Asymmetry	-.004	.986
Left Motor Bank	-.017	.932
Right Motor Bank	-.040	.845
Motor Bank Asymmetry	.033	.869
Left Sensory Bank	-.239	.230
Right Sensory Bank	-.104	.606
Sensory Bank Asymmetry	-.150	.457
Left Olfactory Sulcus	.001	.995
Right Olfactory Sulcus	-.201	.324
Olfactory Sulcus Asymmetry	.280	.166
Left Brain Volume	.014	.943
Right Brain Volume	.090	.657
Total Brain Volume	.056	.781

C-7. Multiple Regression Predicting Phase 2 Word Attack Performance Children With a Right- Hand Preference (n=22).

	R=.718 Rsq=.515 F=9.55, p=.001	
SES	Std. Beta=-.558	t=-3.35, p=.004
MBA	Std. Beta= .556	t= 3.34, p=.004

C-8. Multiple Regression Predicting Phase 2 Word Identification Performance Children With a Right-Hand Preference (n=22).

	R=.714 Rsq=.510 F=9.37, p=.002	
SES	Std. Beta=-.554	t=-3.31, p=.004
MBA	Std. Beta= .555	t= 3.32, p=.004

C-9. Multiple Regression Predicting Phase 2 Passage Comprehension Performance Children With a Right-Hand Preference (n=22).

	R=.777 Rsq=.603 F=13.67, p<.000	
SES	Std. Beta=-.600	t=-3.98, p=.001
MBA	Std. Beta= .606	t= 4.02, p=.001

C-10. Phase 3 (sixth grade) Correlations between Neuroanatomical and Reading Skill Variables in Right-Handed Children (n=27).

	PHRA	PARA	MBA	SBA	IFGA	OSA
Word Attack	**r=.399** **p=.039**	r=-.294 ns	**r=.382** **p=.049**	r=.226 ns	r=.165 ns	r=-.024 ns
Word ID	**r=.430** **p=.025**	**r=-.478** **p=.012**	**r=.390** **p=.044**	r=.355 p=.069	r=-.035 ns	r=-.116 ns
Passage Comp.	r=.373 p=.055	**r=-.381** **p=.050**	r=.274 ns	**r=.496** **p=.009**	r=.005 ns	r=-.039 ns
Phoneme Reversal	**r=.418** **p=.030**	**r=-.475** **p=.012**	r=.268 ns	r=.347 p=.076	r=-.123 ns	r=-.043 ns
LACT	r=.258 ns	r=-.266 ns	r=.168 ns	r=.203 ns	r=-.148 ns	r=.005 ns
Digit Span (forward)	r=.349 p=.075	**r=-.411** **p=.033**	r=.300 ns	r=.305 ns	r=-.215 ns	**r=.392** **p=.047**
RAN colors	r=-.096 ns	r=.359 p=.066	r=-.053 ns	r=.169 ns	r=-.059 ns	r=.352 p=.078

C-11. Phase 3 (sixth grade) Correlations between Neuroanatomical and Reading Skill Variables in Right-Handed Children Not Receiving Lunch Subsidy (n=17).

	PHRA	PARA	MBA	SBA	IFGA	OSA
Word Attack	r=.291 ns	r=-.307 ns	**r=.491** **p=.045**	r=.140 ns	r=.269 ns	r=.030 ns
Word ID	r=.435 p=.081	**r=-.559** **p=.020**	**r=.634** **p=.006**	r=.400 ns	r=.040 ns	r=-.033 ns
Passage Comp.	**r=.532** **p=.028**	**r=-.526** **p=.030**	r=.464 p=.060	**r=.675** **p=.003**	r=.257 ns	r=.223 ns
Phoneme Reversal	**r=.517** **p=.033**	**r=-.580** **p=.015**	r=.468 p=.058	r=.418 p=.095	r=-.068 ns	r=.090 ns
LACT	**r=.506** **p=.054**	**r=-.622** **p=.013**	r=.476 p=.073	r=.181 ns	r=.041 ns	r=.219 ns
Digit Span (forward)	r=.253 ns	**r=-.481** **p=.051**	r=.201 ns	r=.226 ns	r=-.355 ns	**r=.541** **p=.030**
RAN colors	r=.116 ns	r=.299 ns	r=-.387 ns	r=.004 ns	r=-.092 ns	r=.436 p=.091

C-12. Phase 3 (sixth grade) Correlations between Neuroanatomical and Reading Skill Variables in Right-Handed Children Receiving Lunch Subsidy (n=10).

	PHRA	PARA	MBA	SBA	IFGA	OSA
Word Attack	**r= .684** **p=.029**	r=-.161 ns	r= .335 ns	r=.272 ns	r= .341 ns	r=.418 ns
Word ID	**r=.848** **p=.002**	r=-.303 ns	r= .142 ns	r=.123 ns	r= .384 ns	r=.605 p=.064
Passage Comp.	r=.596 p=.069	r=.003 ns	r= .292 ns	r=.157 ns	r=-.005 ns	r=.245 ns
Phoneme Reversal	**r=.647** **p=.043**	r=-.313 ns	r= .147 ns	r=.083 ns	r= .274 ns	**r=.671** **p=.034**
LACT	r=.106 ns	r=.603 p=.065	r=-.100 ns	r=-.058 ns	r= .002 ns	r=.419 ns
Digit SPAN (forward)	r=.484 ns	r=-.247 ns	r= .507 ns	r=.413 ns	r= .195 ns	r=.296 ns
RAN colors	r=-.282 ns	r=.422 ns	r= .321 ns	r=.495 ns	r=-.153 ns	r=.204 ns

C-13. Phase 3 (sixth grade) Correlations between Neuroanatomical and Reading Skill Variables in Non-Right-Handed Children (n=12).

	PHRA	PARA	MBA	SBA	IFGA	OSA
Word Attack	r=-.437 ns	r=.554 p=.060	r=-.375 ns	r=-.390 ns	r= .339 ns	r=-.474 ns
Word ID	**r=-.609** **p=.036**	**r=.577** **p=.050**	r=-.235 ns	r= .320 ns	r= .482 ns	r=-.211 ns
Passage Comp	r= .053 ns	r=.151 ns	r=-.109 ns	r= .029 ns	r= .427 ns	r=-.226 ns
Phoneme Reversal	r=-.387 ns	r=.375 ns	r=-.280 ns	r=-.169 ns	r=-.139 ns	r=-.431 ns
LACT	r=-.239 ns	r=.164 ns	r=-.276 ns	r=-.220 ns	r= .025 ns	r=-.162 ns
Digit Span (forward)	r=-.320 ns	r=.110 ns	r= .468 ns	r= .316 ns	r=-.439 ns	r=-.242 ns
RAN colors	r= .207 ns	r=-.105 ns	r= .094 ns	r= .060 ns	r= .090 ns	r=.045 ns

C-14. Hypothesis 5 ANOVA Results for all Subjects in The Low vs High Reading Skill Development Groups

	df	F	Sig.
PHRA	(1,38)	1.966	0.169
MBA	(1,38)	1.359	0.251
SBA	(1,38)	0.243	0.625
OSA	(1,38)	0.038	0.846
PARA	(1,38)	0.169	0.683
IFGA	(1,38)	0.291	0.593

LIST OF REFERENCES

Adams, M. J. (1990). Beginning to Read: Thinking and Learning About Print. Cambridge, MA, MIT Press.

Alexander, K. L. and D. R. Entwisle (1988). “Achievement in the first 2 years of school: patterns and processes.” Monogr Soc Res Child Dev **53**(2): 1-157.

Amunts, K., Schlaug, G., Schleicher, A., Steinmetz, H., Dabringhaus, A., Roland, P., Zilles, K. (1996). “Asymmetry in the Human Motor Cortex and Handedness.” Neuroimage **4**(3): 216-22.

Annett, M. (1970). “Classification of handedness by association analysis.” British Journal of Psychology **61**: 303-321.

Annett, M. (1976). “Hand preference and the laterality of cerebral speech.” Cortex **11**(4): 305-328.

Baddeley, A. (1995). “Working memory.” The Cognitive Neurosciences Cambridge, MA, MIT Press : 755-764.

Bates, E., Thal, D., Trauner, D., Fenson, J., Aram, D., Eilele, J., Nass, R. (1994). From first words to grammar in children with focal brain injury. Project in Cognitive and Neural Development Technical Report CND-9405.

Baydar, N., Brooks-Gunn, J. , Furstenber, F. (1993). “Early warning signs of functional illiteracy: predictors in childhood and adolescence.” Child Dev **64**(3): 815-29.

Belger, A., Puce, A., Krystal, J., Gore, J., Goldman-Rakic, P., McCarthy, G. (1998). “Dissociation of mnemonic and perceptual processes during spatial and nonspatial working memory using fMRI.” Hum Brain Mapp 6(1):14-32.

Berent, I., and C. Perfetti (1995). “A rose is a REEZ: The two-cycles model of phonological assembly in reading English.” Psychological Review **102**: 146-184.

Berge-Lefranc, J., Jay, R., Massacrier, A., Cau, P., Mattei, M., Bauer, S., Marsollier, C., Berta, P., Fontes, M. (1996). "Characterization of the human jumonji gene." Hum Mol Genet **5**(10): 1637-41.

Binder, J., Swanson, S., Hammeke, T., Morris, G., Mueller, W., Fischer, M., Benbadis S., Frost, J., Rao, S., Haughton, V. (1996). "Determination of language dominance using functional MRI: a comparison with the Wada test." Neurology **46**(4): 978-84.

Binder, J., Hammeke, T., Rao, S., Cox, R. (1996). "Function of the left planum temporale in auditory and linguistic processing." Brain **119**: 1239-1247.

Blachman, B. A. (1991). "Early intervention for children's reading problems: Clinical applications of the research in phonological awareness." Topics in Language Disorders: Language-Disorders.

Blatchford, P. and C. Farquhar (1988). "Factors influencing successful learning in the early school years: Recent research in infant schools in inner London." Educational and Child Psychology: Child-Psychology.

Blumstein, S. E. (1994). "Impairments of speech production and speech perception in aphasia." Philosophical Transactions of the Royal Society of London. B. **346**: 29-36.

Blumstein, S., Baum, S., Waldstein, R., Katz, D. (1994). "The role of lexical status on the phonetic categorization of speech in aphasia ." Brain and Language **46**: 181-197.

Bodurtha, J., Chen, C., Mosteller, M., Nance, W., Schieken, R., Segrest, J. (1991). "Genetic and environmental contributions to cholesterol and its subfractions in 11-year-old twins. The Medical College of Virginia Twin Study." Arterioscler Thromb **11**(4): 844-50.

Bowers, P. G. and M. Wolf (1993). "Theoretical links among naming speed, precise timing mechanisms and orthographic skill in dyslexia." Reading & Writing **5**(1): 69-85.

Bradley, L. and P. E. Bryant (1983). "Categorizing sounds and learning to read: A causal connection." Nature **301**(5899), 419-421.

Brenowitz, E., Baptista, L., Lent, K., Wingfield, J. (1998). "Seasonal plasticity of the song control system in wild Nuttall's white- crowned sparrows." J Neurobiol **34**(1): 69-82.

Brenowitz, E., Lent, K., Kroodsma, D. (1995). "Brain space for learned song in birds develops independently of song learning." J Neurosci **15**(9): 6281-6.

Byrne, M., Crowe, T., Hale, S., Meek, E., Epps, E. (1996). "Metalinguistic and pragmatic abilities of participants in adult literacy programs." J Commun Disord **29**(1): 37-49.

Cardon, L., Smith, S., Fulker, D., Kimberling, W., Pennington, B., DeFries, J. (1994). "Quantitative trait locus for reading disability on chromosome 6 [see comments]." Science **266**(5183): 276-9.

Cardon, L., Smith, S., Fulker, D., Kimberling, W., Pennington, B., DeFries, J. (1995). "Quantitative trait locus for reading disability: correction [letter]." Science **268**(5217): 1553.

Charles, P., Abou-Khalil, B., Atkinson, D., Bakar, M., Mayville, C., Kirshner, H. (1997). "Occipital pole area and language dominance." J Neuroimaging **7**(2):89-91.

Chi, J., Dooling, E., Gilles, F. (1977). "Left-right asymmetries of the temporal speech areas of the human fetus." Arch Neurol **34**(6): 346-348.

Church, M. W. and J. A. Kaltenbach (1997). "Hearing, speech, language, and vestibular disorders in the fetal alcohol syndrome: a literature review." Alcohol Clin Exp Res **21**(3): 495-512.

Clark, M. M. and E. Plante (1998). "Morphology of the inferior frontal gyrus in developmentally language- disordered adults." Brain Lang **61**(2): 288-303.

Cooper, R. P. and R. N. Aslin (1994). "Developmental differences in infant attention to the spectral properties of infant-directed speech." Child Dev **65**(6): 1663-77.

Cornwall, A. (1992). "The relationship of phonological awareness, rapid naming, and verbal memory to severe reading and spelling disability." J Learn Disabil **25**(8): 532-8.

Coslett, H. B. and N. Monsul (1994). "Reading with the right hemisphere: evidence from transcranial magnetic stimulation." Brain Lang **46**(2): 198-211.

Damasio, H., Grabowski, T., Tranel, D., Hichwa, R., Damasio, A. (1996). "A neural basis for lexical retrieval." Nature **380**(6574): 499-505.

Davies, A. F.,Olavesen, M., Stephens, R., Davidson, R., Delneste, D., Van Regemorter N., Vamos, E., Flinter, F., Abusaad, I., Ragoussis, J. (1996). "A detailed investigation of two cases exhibiting characteristics of the 6p deletion syndrome." Hum Genet **98**(4): 454-9.

de Jong, P. F. (1993). "The relationship between students' behaviour at home and attention and achievement in elementary school." Br J Educ Psychol **63**(Pt 2): 201-13.

DeFries, J., Gillis, J., Wadsworth, S. (1993). "Genes and gender: a twin study of reading disability." Dyslexia and Development: Neurobiological Aspects of Extraordinary Brains. Ed. Galaburda, A.M. Harvard Unviersity Press, Cambridge, MA.: p 187-204.

DeFries, J., Fulker, D., LaBuda, M. (1987). Evidence for a genetic aetiology in reading disability of twins. Nature **329**(6139): 537-539.

Denckla, M. B. and R. G. Rudel (1976). "Rapid "automatized" naming (R.A.N): dyslexia differentiated from other learning disabilities." Neuropsychologia **14**(4): 471-479.

Diamond, M., Law, F., Rhodes, H., Lindner, B., Rosenzweig, M., Krech, D., Bennett E. (1966). "Increases in cortical depth and glia numbers in rats subjected to enriched environment." J Comp Neurol **128**(1): 117-26.

Ehret, G. (1987). "Left hemisphere advantage in the mouse brain for recognizing ultrasonic communication calls." Nature **325**(6101): 249-51.

Ehri, L. C. (1989). "The development of spelling knowledge and its role in reading acquisition and reading disability." J Learn Disabil **22**(6): 356-65.

Emde, R. N., R. Plomin, et al. (1992). "Temperament, emotion, and cognition at fourteen months: the MacArthur Longitudinal Twin Study." Child Dev **63**(6): 1437-55.

Felton, R., Naylor, C., Wood, F. (1990). "Neuropsychological profile of adult dyslexics." Brain Lang **39**(4): 485-97.

Fernald, A. (1989). "Intonation and communicative intent in mothers' speech to infants: is the melody the message?" Child Dev **60**(6): 1497-510.

Fernald, A. (1993). "Human maternal vocalizations to infants as biologically relevant signals: An evolutionary perspective ." The adapted mind: Evolutionary psychology and the generation of culture. Eds. Barkow, J.H., Cosmides, L., Tooby, J. Oxford University Press, NY, NY: 51-94.

Ferri, B., Gregg, N., Heggoy, S. (1997). "Profiles of college students demonstrating learning disabilities with and without giftedness." J Learn Disabil **30**(5): 552-9.

Foundas, A., Leonard, C.M., Gilmore, R., Fennell, E. (1994). "Planum temporale asymmetry and language dominance." Neuropsychologia **32**(10): 1225-1231.

Foundas A., Leonard, C., Gilmore, R.., Fennell, E., Heilman, K. (1996). "Pars triangularis asymmetry and language dominance." Proc Natl Acad Sci U S A **93**(2): 719-22.

Foundas, A., Leonard, C., Heilman, K. (1995). "Morphologic cerebral asymmetries and handedness: The pars triangularis and planum temporale." Archives of Neurology **52**(5): 501-508.

Fowler, M. G. and A. W. Cross (1986). "Preschool risk factors as predictors of early school performance." J Dev Behav Pediatr **7**(4): 237-41.

Fox, B. (1975). " Analysing spoken language into words, syllables, and phonemes: A developmental study." Journal of Psycholinguistic Research **4**(4): 331-342.

Gabbard, C. and S. Hart (1995). "Foot performance of right- and left-handers: a question of environmental influence." Percept Mot Skills **80**(2): 671-4.

Galaburda, A., Rosen, G., Aboitiz, F., Geschwind, N. (1985). "Developmental dyslexia: Four consecutive cases with cortical anomalies." Annals of Neurology **18**: 222-233.

Galaburda, A. (1980). "Cytoarchitectonic organization of the human auditory cortex."Journal of Comparative Neurology **190**: 597-610.

Gallagher, T. M. and K. L. Watkin (1997). "3D ultrasonic fetal neuroimaging and familial language disorders: In utero brain development." J. Neurolinguistics **10**(2-3): 187-201.

Gangestad, S., Yeo, R., Shaw, P., Thoma, R. (1996). "Human leukocyte antigens and hand preference: Preliminary observations." Neuropsychology **10**(3): 423-428.

Gannon, P., Holloway, R., Broadfield, D., Braun, A. (1998). Asymmetry of chimpanzee planum temporale: humanlike pattern of Wernicke's brain language area homolog. Science **279** (5348): 220-2.

Gauger, L., Lombardino, L., Leonard, C. (1997). "Brain morphology in children with specific language impairment." J Speech Lang Hear Res **40**(6): 1272-84.

Geschwind, N., and W. Levitsky (1968). "Human brain: left-right asymmetries in temporal speech region." Science **161**(837):186-187.

Goldman, P. S. and T. W. Galkin (1978). "Prenatal removal of frontal association cortex in the fetal rhesus monkey: anatomical and functional consequences in postnatal life." Brain Res **152**(3): 451-85.

Goldman-Rakic, P. S. (1988). "Topography of cognition: parallel distributed networks in primate association cortex." Annual Review of Neuroscience **11**: 137-156.

Goldman-Rakic, P. S. (1990). "Cellular and circuit basis of working memory in prefrontal cortex of nonhuman primates." Prog Brain Res **85**: 325-35.

Govind, C. K. and D. J. Potter (1987). "Development of bilateral asymmetry in sensory innervation to lobster claws." Brain Res **432**(1): 131-9.

Greenough, W., Hwang, H., Gorman, C. (1985). "Evidence for active synapse formation or altered postsynaptic metabolism in visual cortex of rats reared in complex environments." Proc Natl Acad Sci U S A **82**(13): 4549-52.

Greenough, W., McDonald, J., Parnisari, R., Camel, J. (1986). "Environmental conditions modulate degeneration and new dendrite growth in cerebellum of senescent rats." Brain Res **380**(1): 136-43.

Grigorenko, E., Wood, F., Meyer, M., Hart, L., Speed, W., Shuster, A., Pauls, D. (1997). "Susceptibility loci for distinct components of developmental dyslexia on chromosomes 6 and 15 [see comments]." Am J Hum Genet **60**(1): 27-39.

Grisham, W. and A. P. Arnold (1995). "A direct comparison of the masculinizing effects of testosterone, androstenedione, estrogen, and progesterone on the development of the zebra finch song system." J Neurobiol **26**(2): 163-70.

Gulledge, C. C. and P. Deviche (1997). "Androgen control of vocal control region volumes in a wild migratory songbird (Junco hyemalis) is region and possibly age dependent." J Neurobiol **32**(4): 391-402.

Habib, M. R., F.; Levier, O.; Khalil, R., Salamon, G. (1995). "Diverging asymmetries of temperoparietal cortical areas. A reappraisal of Geschwind-Galaburda theory." Brain and Language **48**: 238-258.

Hallgren, B. (1950). Specific dyslexia ("congenital word-blindness"): a clinical and genetic study. Acta Psychiatrica et Neurologica (KjoBenhavn) Suppl. **65**: 287.

Heilman, K., Bowers, D., Valenstein, E., Watson, R. (1986). "The right hemisphere: neuropsychological functions." J Neurosurg **64**(5): 693-704.

Hernandez, S., Camacho Rosales, R., Nieto, A., Barroso, J. (1997). "Cerebral asymmetry and reading performance: Effect of language lateralization and hand preference." Child Neuropsychology **3**(3): 206-225.

Herrnstein, R. J. and C. A. Murray (1994). The bell curve : intelligence and class structure in American life. New York, Free Press.

Jackson, T. and E. Plante (1996). "Gyral morphology in the posterior Sylvian region in families affected by developmental language disorder." Neuropsychol Rev **6**(2): 81-94.

Jernigan, T., Hesselink, J., Tallal, P. (1991). "Maturation of human cerebrum observed in vivo during adolescence." Brain **114**: 2037-2049.

Johnson, J. S. and E. L. Newport (1989). "Critical period effects in second language learning: the influence of maturational state on the acquisition of English as a second language." Cognit Psychol **21**(1): 60-99.

Juel, C. and J. A. Leavell (1988). "Retention and nonretention of at-risk readers in first grade and their subsequent reading achievement." J Learn Disabil **21**(9): 571-80.

Karni, A., Meyer, G., Jezzard, P., Adams, M., Turner, R., Ungerleider L. (1995). "Functional MRI evidence for adult motor cortex plasticity during motor skill learning." Nature **377**(6545): 155-8.

Kertesz, A., Polk, M., Black, S., Howell, J. (1992). "Anatomical asymmetries and functional laterali,ty." Brain **115**(Pt 2): 589-605.

Konishi, M, (1985). Birdsong: From behavior to neuron. Annual Review of Neuroscience 8: 125-170.

Kuhl, P., Andruski, J., Chistovich, I., Chistovich, L., Kozhevnikova, E., Ryskina, V., Stolyarova, E., Sundberg, U., Lacerda, F. (1997). "Cross-language analysis of phonetic units in language addressed to infants." Science **277**(5326): 684-6.

Kuhl, P., Lacerda, F., Stevens, K., Lindblom, B. (1992). "Linguistic experience alters phonetic perception in infants by six months of age." Science **255**: 606-608.

Kulynych, J., Fantre, B., Jones, D., Weinberger, D. (1995). "Normal asymmetry of the planum temporale in patients with schizophrenia. Three dimensional cortical morphometry with mri." British Journal of Psychiatry **166**: 742-749.

LeMay, M. (1976). "Morphological cerebral asymmetries of modern man, fossil man, and nonhuman primate." Ann N Y Acad Sci **280**: 349-66.

Leonard, C. (1996). "Structural variation in the developing and mature brain: Noise or signal." Developmental neuroimaging: Mapping the development of brain and behavior. Ed. R.W., Thatcher, G.R., Lyon, J. Rumsey, N. Krasnegorieds. Academic Press, S.D., CA: 207-231.

Leonard, C. (1997). "Language and the prefrontal cortex." Development of the prefrontal cortex: Evolution, neurobiology, and behavior. Eds. Krasnegor, N., Lyon, G. et-al. Baltimore, MD: Paul H. Brookes Publishing Co. 141-166.

Leonard, C., Lombardino, L., Freeman, A., Mohr, C., Kranzler, J. (1988). "Neurobiological Foundations of Reading Disabilities." Annual meeting, Society for the Scientific Study of Reading.

Leonard, C., Mercado, L., Browd, S., Breier, J., Agee, O. (1996). "Cerebral asymmetry and cognitive development in children: A magnetic resonance imaging study." Psychological Science **7**: 79-85.

Leonard, C. M., Voeller, K., Lombardino, L., Morris, M., Hynd, G., Alexander, A., Andersen, H., Garofalakis, M., Honeyman, J., Mao, J. (1993). "Anomalous cerebral structure in dyslexia revealed with magnetic resonance imaging [see comments]." Arch Neurol **50**(5): 461-9.

Levin, M. (1997). "Left-right asymmetry in vertebrate embryogenesis." Bioessays **19**(4): 287-96.

Liberman, I., Fischer, F., Carter, B. (1974). "Explicit syllable and phoneme segmentation in the young child." Journal of Experimental Child Psychology **18**: 201-212.

Light, J., Defries, J. Olson, R. (1998). "Multivariate behavioral genetic analysis of achievement and cognitive measures in reading-disabled and control twin pairs." Hum Biol **70**(2): 215-37.

Lombardino, L. Bedford, T., Fortier, C., Carter, J., Brandi, J. (1997). "Invented spelling: Developmental patterns in kindergarten children and guidelines for early literacy intervention." Language, Speech and Hearing Services in Schools **28**(4): 333-343.

Lombardino, L., Morris, D., Mercado, L., Defillipo, F., Sarisky, C., Montgomery, A. (in press). The Early Reading Screening Instrument": A methods for identifying kindergarteners at risk for learning to read. International Journal of Communication Disorders.

Lubs, H., Smith, S., Kimberling, W., Pennington, B., Gross-Glenn, K., Duara, R. (1988). "Dyslexia subtypes: genetics, behavior, and brain imaging." Res Publ Assoc Res Nerv Ment Dis **66**: 139-47.

Luria, A. (1962). Higher Cortical Functions in Man. New York, Basic Books, Inc.

MacDonald, G. W. and A. Cornwall (1995). "The relationship between phonological awareness and reading and spelling achievement eleven years later." J Learn Disabil **28**(8): 523-7.

McBride-Chang, C. (1996). "Models of speech perception and phonological processing in reading." Child Dev **67**(4): 1836-56.

McGuire, P., Silbersweig, D., Wright, I., Murray, R., Frackowiak, R., Frith, C. (1996). "Functional anatomy of inner speech and auditory verbal imagery." Psychol Med 26(1): 29-38.

McManus, I. C. (1981). "Handedness and birth stress." Psychol Med **11**(3): 485-96.

McManus, I. C. (1995). "Familial sinistrality: the utility of calculating exact genotype probabilities for individuals." Cortex **31**(1): 3-24.

Merzenich, M. M. and J. F. Brugge (1973). "Representation of the cochlear partition of the superior temporal plane of the macaque monkey." Brain Res **50**(2): 275-96.

Merzenich, M., Johnston, P., Schreiner, C., Miller, S., Tallal, P. (1996). "Temporal processing deficits of language-learning impaired children ameliorated by training." Science **271**: 77-81.

Mody, M., Studdert-Kennedy, M., Brady, S. (1997). Speech perception deficits in poor readers: auditory processing or phonological coding? J Exp Child Psychol **64**(2): 199-231.

Naslund, J. C. and W. Schneider (1996). "Kindergarten letter knowledge, phonological skills, and memory processes: relative effects on early literacy." J Exp Child Psychol **62**(1): 30-59.

Nottebohm, F., Tegner, M., Leonard, C. (1976). "Central control of song in the canary." Journal of Comparative Neurology **165**: 457-486.

Nudo, R., Milliken, G., Jenkins, W., Merzenich, M. (1996). "Use-dependent alterations of movement representations in primary motor cortex of adult squirrel monkeys." J Neurosci **16**(2): 785-807.

Oakland, T. (1998). "Neurobiological foundations of reading disabilities: Part III; College students with compensated dyslexia do not have anomalous asymmetry of the planum." Annual meeting, Society for the Scientific Study of Reading.

Oerlemans, M., Dodd, B. (1993). Development of spelling ability and letter-sound orientation in primary school children. European Journal of Disorders of Communication **28**(4): 349-367.

Ojemann, G., Letttich, E., Haglund, M. (1988). "Neuronal activity in human lateral temporal cortex relatied to short-term verbal memory, naming and reading." Brain **111**: 1383-1403.

Olson, R., Wise, B., Conners, F., Rack, J., Fulker, D. (1989). "Specific deficits in component reading and language skills: genetic and environmental influences." J Learn Disabil **22**(6): 339-48.

Ong, W. Y. and L. J. Garey (1990). "Neuronal architecture of the human temporal cortex." Anat Embryol **181**(4): 351-64.

Orlebeke, J., Knol, D., Koopmans, J., Boomsma, D., Bleker, O. (1996). "Left-handedness in twins: genes or environment?" Cortex **32**(3): 479-90.

Pandya, D. N. and F. Sanides (1973). "Architectonic parcellation of the temporal operculum in rhesus monkey and its projection pattern." Z Anat Entwicklungsgesch **139**(2): 127-61.

Pascual-Leone, A. and F. Torres (1993). "Plasticity of the sensorimotor cortex representation of the reading finger in Braille readers." Brain **116**: 39-52.

Paulesu, E., Frith, C., Frackowiak, R. (1993). "The neural correlates of the verbal component of working memory [see comments]." Nature 362(6418): 342-5.

Paulesu, E., Goldacre, B., Scifo, P., Cappa, S., Gilardi, M., Castiglioni, I., Perani, D., Fazio, F. (1997). "Functional heterogeneity of left inferior frontal cortex as revealed by fMRI." Neuroreport **8**(8): 2011-7.

Pennington, B. F. and S. D. Smith (1997). "Genetic analysis of dyslexia and other complex behavioral phenotypes." Curr Opin Pediatr **9**(6): 636-41.

Pennington, B., Van Orden, G., Smith, S., Green, P., Haith, M. (1990). "Phonological processing skills and deficits in adult dyslexics." Child Dev **61**(6): 1753-78.

Peralta de Mendoza, O. A. (1995). "Developmental changes and socioeconomic differences in mother infant picture book reading." European J. Psych. Educ. **10**(3): 261-172.

Petersen, M., Zoloth, S., Moody, D., Stebbins, W. (1978). "Neural lateralization of species-specific vocalizations by Japanese macaques." Science **202**: 324-326.

Petersen, S., Fox, P., Posner, M., Mintun, M., Raichle, M. (1988). "Positron emission tomographic studies of the cortical anatomy of single-word processing." Nature **331**(6157): 585-589.

Petersen, S., Fox, P., Snyder, A., Raichle, M. (1990). "Activation of extrastriate and frontal cortical areas by visual words and word-like stimuli." Science **249**(4972), 1041-1044.

Petrill, S., Saudino, K., Cherny, S., Emde, R., Fulker, D., Hewitt, J., Plomin, R. (1998). "Exploring the genetic and environmental etiology of high general cognitive ability in fourteen- to thirty-six-month-old twins." Child Dev **69**(1): 68-74.

Pieniadz, J. M. and M. A. Naeser (1984). "Computed tomographic scan cerebral asymmetries and morphologic brain asymmetries. Correlation in the same cases post mortem." Arch Neurol **41**(4): 403-9.

Pihan, H., Altenmuller, E., Ackermann, H. (1997). "The cortical processing of perceived emotion: a DC-potential study on affective speech prosody." Neuroreport **8**(3): 623-7.

Plante, E., Swisher, L., Vance, R. (1989). "Anatomical correlates of normal and impaired language in a set of dizygotic twins." Brain Lang **37**(4): 643-55.

Plante, E., Vance, R., Rapcsak, S. (1991). "MRI findings in boys with specific language impairment." Brain & Language **41**: 52-66.

Plomin, R. and J. C. Loehlin (1989). "Direct and indirect IQ heritability estimates: a puzzle." Behav Genet **19**(3): 331-42.

Plomin, R. and L. A. Thompson (1993). "Genetics and high cognitive ability." Ciba Found Symp **178**: 67-79.

Provins, K. A. (1997). "Handedness and speech: a critical reappraisal of the role of genetic and environmental factors in the cerebral lateralization of function." Psychol Rev **104**(3): 554-71.

Pugh, K, Constable, R., Shaywitz, S., Skudlarski, P., Fulbright, R., Brone, R., Shankweiler, D., Katz, L., Fletcher, J., Gore, J. (1996). "Cerebral organization of component processes in reading." Brain **119**: 1231-1238.

Rasmussen, T., and Milner, B. (1977). "The role of early left-brain injury in determining lateralization of cerebral speech functions." Ann NY Acad Sci 30(299):355-69.

Ratcliff, G., Dila, C., Taylor, L., Milner, B. (1980). "The morphological asymmetry of the hemispheres and cerebral dominance for speech: a possible relationship." Brain Lang **11**(1): 87-98.

Ratusnik, D. L. and R. A. Koenigsknecht (1975). "Influence of certain clinical variables on black preschoolers' nonstandard phonological and grammatical performance." J Commun Disord **8**(4): 281-97.

Reed, M. A. (1989). "Speech perception and the discrimination of brief auditory cues in reading disabled children." J Exp Child Psychol **48**(2): 270-92.

Reilly, J.S., Bates, E., Marchman, V. (1995). Narrative discourse in children with early focal brain injury. Project in Cognitive and Neural Development Technical Report CND-9504.

Repetto, G. , White, L., Bader, P., Johnson, D., Knoll, J. (1998). "Interstitial duplications of chromosome region 15q11q13: clinical and molecular characterization [In Process Citation]." Am J Med Genet **79**(2): 82-9.

Rosen, G. D. (1996). "Cellular, morphometric, ontogenetic and connectional substrates of anatomical asymmetry." Neurosci Biobehav Rev **20**(4): 607-15.

Rumsey, J., Nace, K., Donohue, B., Wise, D., Maisog, J., Andreason, P. (1997). "A magnetic resonance imaging study of planum temporale asymmetry in men with developmental dyslexia." Arch Neurol **54**(12): 1481-9.

Sahai, H. (1989). "Relations of sociodemographic variables and cognitive ability: a comparative analysis of the cognitive scores of high school seniors." Percept Mot Skills **69**(3 Pt 2): 1139-57.

Satz, P., Strauss, E., Wada, J., Orsini, D. (1988). "Some correlates of intra- and interhemispheric speech organization after left focal brain injury." Neuropsychologia **26**(2): 345-50.

Satz, P., Strauss, E., Whitaker, H. (1990). The ontogeny of hemispheric specialization: Some old hypotheses revisited. Brain and Language 38(4), 596-614.

Scarr, S. and R. A. Weinberg (1983). "The Minnesota Adoption Studies: genetic differences and malleability." Child Dev **54**(2): 260-7.

Schieken, R., Eaves, L., Hewitt, J., Mosteller, M., Bodurtha, J., Moskowitz, W., Nance, W. (1989). "Univariate genetic analysis of blood pressure in children (the Medical College of Virginia Twin Study)." Am J Cardiol **64**(19): 1333-7.

Schlaug, G., Huang, Y., Steinmetz, H. (1995). "In vivo evidence of structural brain asymmetry in musicians." Science **267**: 699-701.

Schwarz, I. M. and L. J. Rogers (1992). "Testosterone: a role in the development of brain asymmetry in the chick." Neurosci Lett **146**(2): 167-70.

Seldon, H. L. (1981). "Structure of human auditory cortex. I. Cytoarchitectonics and dendritic distributions." Brain Research **229**: 277-294.

Semrud-Clikeman, M. E. (1990). "Dyslexia and brain morphology: Contributions to disturbances in phonological coding, naming, and reading." Dissertation Abstracts International **51**(4a): 1172.

Sereno, M., Dale, A., Reppas, J., Kwong, K., Belliveau, J., Brady, T., Rosen, B., Tootell, R. (1995). "Borders of multiple visual areas in humans revealed by functional magnetic resonance imaging [see comments]." Science **268**(5212): 889-93.

Shafer, V., Shucard, D., Shucard, J., Gerken, L. (1998). "An electrophysiological study of infants' sensitivity to the sound patterns of English speech [In Process Citation]." J Speech Lang Hear Res **41**(4): 874-86.

Shankweiler, D., Katz, L., Fowler, A., Liberman, A., Brady, S., Thornton, R., Lundquist, E., Dreyer, L., Fletcher, J., Stuebing, K., Shaywitz, S., Shaywitz, B. (1995). "Cognitive profiles of reading-disabled children; Comparison of language skills in phonology, morphology, and syntax." Psychological Science **6**: 149-156.

Share, D. L. (1995). "Phonological recoding and self-teaching: sine qua non of reading acquisition." Cognition **55**(2): 151-218; discussion 219-26.

Shaywitz, S. (1996). "Dyslexia." Scientific American **275**(5): 98-104.

Slavin, M. O. (1985). "A developmental disorder of late adolescence." Int J Psychoanal Psychother **11**: 219-41.

Smith, S., Pennington, B., Kimberling, W., Ing, P. (1990). "Familial dyslexia: use of genetic linkage data to define subtypes." J Am Acad Child Adolesc Psychiatry **29**(2): 204-13.

Snow, C. E. (1983). "Literacy and language: Relationships during the preschool years." Harvard Educational Review: Educational-Review.

Stanovich, K. E. (1988). "Explaining the differences between the dyslexic and the garden-variety poor reader: the phonological-core variable-difference model." J Learn Disabil **21**(10): 590-604.

Stanovich, K., and A.Cunningham (1984). "Relation between early reading acquisition and word decoding with and without context: A longitudinal study of first-grade children." Journal of Educational Psychology **76**(4): 668-677.

Steinmetz, H., Jancke, L., Freund, H. (1991). "Anatomical left-right asymmetry of language related temporal cortex is different in left-and right-handers." Annals of Neurology **29**: 315-319.

Steinschneider, M., Arezzo, J., Vaughan, H. (1993). "Temporal encoding of phonetic features in auditory cortex." Annals of the New York Academy of Sciences **682**: 415-417.

Strauss, E. and B. Goldwater (1992). "Sex differences in interhemispheric reorganization of speech." Neuropsychologia **30**: 353-359.

Tallal, P. (1973). “Developmental aphasia: Impaired rate of nonverbal processing as a function of sensory modality.” Neuropsychologia **11**: 389-398.

Thal, D., and E. Bates (1988). “Language and gesture in late talkers.” J Speech Hear Res **31**(1):115-23.

Tokimura, H., Tokimura, Y., Oliviero, A., Asakura, T., Rothwell, J. (1996). "Speech-induced changes in corticospinal excitability." Ann Neurol **40**(4): 628-34.

Tootell, R., Switkes, E, Silverman, M., Hamilton, S. (1988). “Functional anatomy of macaque striate cortex. II. Retinotopic organization.” J. Neurosci **8**(5); 1531-1568.

Torgesen, J., Wagner, R., Balthazar, M., Davis, C. (1989). “Developmental and individual differences in performance on phonological synthesis tasks.” J Exp Child Psychol **47**(3): 491-505.

Torgesen, J., Wagner, R., Rashotte, C. (1994). “Longitudinal studies of phonological processing and reading.” J Learn Disabil **27**(5): 276-86; discussion 287-91.

Van Essen, D. and J., Gallant (1994). “Neural mechanisms of form and motion processing in the primate visual system.” Neuron **13**(1): 1-10.

Vandenberghe, R., Price, C., Wise, R., Josephs, O., Frackowiak, R. (1996). “Functional anatomy of a common semantic system for words and pictures.” Nature **383**(6597): 254-256.

Vellutino, F., Scanlon, D., Sipay, E., Small, S. (1996). “Cognitive profiles of difficult-to-remediate and readily remediated poor readers: Early intervention as a vehicle for distinguishing between cognitive and experiential deficits as basic causes of specific reading disability.” J. Educ. Psych. **88**(4): 601-638.

Wada, J. A. (1977). “Pre-language and fundamental asymmetry of the infant brain.” Ann NY Acad Sci **299**: 370-9.

Wada, J. A. and A. E. Davis (1977). “Fundamental nature of human infant's brain asymmetry.”Can J Neurol Sci **4**(3): 203-7.

Wagner, R., Torgesen, J., Rashotte, C., Hecht, S., Barker, T., Burgess, S., Donahue J., Garon, T. (1997). “Changing relations between phonological processing abilities and word- level reading as children develop from beginning to skilled readers: a 5-year longitudinal study.” Dev Psychol **33**(3): 468-79.

Walker, D., Greenwood, C., Hart, B., Carta, J. (1994). "Prediction of school outcomes based on early language production and socioeconomic factors." Child Dev **65**(2 Spec No): 606-21.

Warburton., E., Wise, R., Price, C., Weiller, C., Hadar, U., Ramsay, S., Frackowiak, R. (1996). "Noun and verb retrieval by normal subjects. Studies with PET." Brain **119**(Pt 1): 159-79.

Ward, B., Nordeen, E., Nordeen, E. (1998). "Individual variation in neuron number predicts differences in the propensity for avian vocal imitation." Proc Natl Acad Sci U S A **95**(3): 1277-82.

Watkins, K., Vargha-Kadem, F., Ashburner, J., Friston, K., Connelly, A., Gadian, D. (1997). Bilateral abnormality of the Caudate in a Family with an Inherited Speech and Language Disorder. Society for Neuroscience, New Orleans.

Watson, B. (1992). "Auditory temporal acuity in normally achieving and learning-disabled college students." J Speech Hear Res **35**(1): 148-56.

Westergaard, G., Kuhn, H., Suomi, S. (1998). "Bipedal posture and hand preference in humans and other primates." J Comp Psychol **112**(1): 55-64.

Westergaard, G., Kuhn, H., Suomi, S. (1998). "Effects of upright posture on hand preference for reaching vs. the use of probing tools by tufted capuchins (Cebus apella)." Am J Primatol **44**(2): 147-53.

Williams, H., Crane, L., Hale, T., Esposito, M., Nottebohm, F. (1992). "Right-side dominance for song control in the zebra finch." J Neurobiol **23**(8): 1006-20.

Williams, R., Strom, R., Goldowitz, D. (1998). "Natural Variation in Neuron Number in Mice is Linkied to a Major Quantitative Trait Locus on Chr 11." J Neurosci **18**(1): 138-146.

Wise, R., Hadar, U., Howard, D., Patterson, K. (1991). "Language activation studies with positron emission tomography." Ciba Found Symp 163: 218-28.

Witelson, S. F. and W. Pallie (1973). "Left hemisphere specialization for language in the newborn. Neuroanatomical evidence of asymmetry." Brain **96**(3): 641-6.

Wolf, M. (1991). "The word-retrieval deficit hypothesis and developmental dyslexia." Learning and Individual Differences **3**(3): 205-223.

Wolf, M., Bally, H., Morris, R. (1986). "Automaticity, retrieval processes, and reading: A longitudinal study in average and impaired readers." Child Development **57**(4): 988-1000.

Wood, F. (1997). Positron Emission Tomography Studies of Dysleixa-Related Phenotypes. World Congress on Dyslexia, Macedonia, Greece.

Zaidel E. and A. Peters (1981). "Phonological encoding and ideographic reading by the disconnected-right-hemisphere: Two case studies." Brain and Language **14**: 205-234.

Zatorre, R. J. (1988). "Pitch perception of complex tones and human temporal-lobe function." Journal of the Acoustical Society of America **84**: 566-572.

Zatorre, R., Evans, A., Meyer, E. (1994). "Neural mechanisms underlying melodic perception and memory for pitch." J Neurosci **14**(4): 1908-19.

Zilles, K., Dabringhaus, A., Geyer, S., Amunts, K., Qu, M., Schleicher, A., Gilissen, E., Schlaug, G., Steinmetz, H. (1996). "Structural asymmetries in the human forebrain and the forebrain of non- human primates and rats." Neurosci Biobehav Rev **20**(4): 593-605.

Zilles, K. T. (1990). "Cortex." In The Human Nervous System. NY, Academic Press: 757-802.

BIOGRAPHICAL SKETCH

Mark Andrew Eckert was born in Akasambo, Ghana, on May 10, 1970. Mark began his undergraduate work in 1988, at Villanova University, Villanova Pennsylvania. During his undergraduate career he was involved in dolphin cognition research at Kewalo Basin Marine Mammal Laboratory, University of Hawaii and studied the effect of prenatal testosterone on sexually dimorphic nuclei at Villanova University. He completed his undergraduate work at Villanova University in May 1992, when he was awarded his B.A. in psychology. Following graduation, he began work on his M.A. in experimental neuropsychology at George Mason University, Fairfax, Virginia. His master's thesis compared the monoamine neurotransmitter levels of high risk infants to normally developing infants. Mark received his M.A. from George Mason University in August 1994. He began his doctoral work with Dr. Christiana Leonard during the fall of 1994, in the area of psychobiology. Upon receiving his doctoral degree in December 1998, Mark plans to continue research as a postdoctoral research fellow in the area of neurobehavioral genetics at the University of Florida.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Christiana Leonard

Christiana Leonard, Chair
Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Doctor of Philosophy.

Dawn Bowe

Dawn Bowers
Associate Professor of Clinical & Health Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Jeff Far

Jeff Farrar
Associate Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Neil Rowland
Professor of Psychology

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Carol Van Hartesveldt

Carol Van Hartesveldt
Professor of Psychology

This disseration was submitted to the Graduate Faculty of the Department of Psychology in the College of Liberal Arts and Sciences, and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December, 1998

Dean, Graduate School